Solving the battle of post-disaster response and restauration (BPDRR) problem with the aid of multi-phase optimization framework

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ABSTRACT

The Battle of Post-Disaster Response and Restauration (BPDRR) is a challenging optimization problem which requires the restauration of the B-city water distribution network (WDN) after an earthquake. More specifically, the water utility is looking to schedule the available three crews to isolate, repair or replace the damaged pipes to rapidly improve the system's capacity of restoring the service. A many-objective analysis framework is used to identify the best way to respond to the disaster and restore functionality of the water distribution network for each post-earthquake scenario. The many-objective formulation focuses on a suite of six objectives, as follows: (1) time that the hospitals and the firefighting flows are without supply, (2) rapidity of recovery, (3) resilience loss, (4) average time each consumer (node) is without service, (5) number of consumers (nodes) without service for more than 8 consecutive hours, and (6) volume of water lost during the next 7 days after the event. We proposed a multi-phase optimization methodology in combination with manual intervention, which takes the advantage of evolutionary computation as well as engineering experiences. The method consists of three stages: (1) preliminary analysis; (2) sub-optimization; and (3) global optimization. A pressure-driven model is used to enable the pipe-breaking analysis as it can simulate the outflows and water shortages induced by pipe breaks. Such a strategy is expected to find feasible and optimal solutions in an efficient manner. The improved genetic algorithm is applied to solve the optimization problem. Details of the recovery strategy resulting from the proposed optimization method are provided. The results provide some value insights on how to make considerate optimal recovery plan. For instance, certain broken pipes have to be fixed between particular time stamps to avoid negative affects on the level of services at some critical facilities.

Keywords: Water distribution systems; Pipe-breaking analysis; Post-disaster response and restauration

INTRODUCTION

Water distribution systems (WDSs), the lifelines of a city, are designed to provide water supply without any failure of service under normal conditions. However, as abnormal conditions in the systems are unavoidable, increasingly researches have started exploring how to minimize level of service failure magnitude and duration over the system's design life when subject to exceptional conditions, i.e. to improve the resilience (Butler et al. 2016). In this regard, effective emergency planning of interventions is a key to enable timely recovery of systems subject to failures and meanwhile minimize the failure impacts.

Studies on WDS resilience is at an early stage as most of current researches focus on assessment of resilience in WDS (Kanta, 2006; Yazdani et al. 2011; Kanta and Brumbelow, 2013; Berardi, 2014; Gay and Sinha, 2014; Gheisi and Naser, 2014; Butler et al. 2016; Cimellaro, 2016; Pandit and Crittenden, 2016; Klise, 2017; Piller et al. 2017; Shuang et al. 2017; Shin et al. 2018). Specifically, resilience of the original WDS and alternative designs is evaluated to gain understanding of the inherent resilience of the underlying system. For instance, Pandit and Crittenden (2016) developed an index of resilience that is a weighted summation of six topological attributes of water distribution systems. Through evaluating alternative topologies designed for the Anytown, it is found that despite there is a trade-off between resilience and efficiency, resilience of the system can be improved through a better topology without increasing investment. Cimellaro et al (2016) proposed a resilience index to evaluate the capability of a WDS to: (1) delivering a certain demand of water with an acceptable level of pressure and quality, and (2) the restoration process following an extreme event. The index was applied to evaluate different disruptive scenarios and restoration plans of a town-level WDS in Italy. The results revealed pros and cons of the different restoration plans and the importance of partitioning network into districts to reduce the lack of services. Further, it shows the limitation of using a global index as some trends cannot be captured unless separate indexes are used. Using complex network metrics, Yazdani et al. (2011) examined the resilience of different expansion options for a WDS in a growing city.

Some assessments focus on resilience of WDS to specific failures. Gheisi and Naser (2014) explored WDS's resilience in relation to pipe failure mode. In their study, the performance of alternative WDS layout designs was tested under an increasing number of simultaneous failed pipes. The corresponding frequency and magnitude of impacts was then measured. Berardi et al. (2014) applied an evolutionary algorithm to identify scenarios that have a minimum fraction of failed pipes, yet result in maximum shortage of water supply (e.g. isolation of connections to all water sources). For the same purpose, Kanta (2006), Bristow et al. (2007) and Kanta and Brumbelow (2013) studied pipe failure mode during firefighting and identified its maximum strain. However, these studies did not model the recovery of the system from failure or measure the impact duration. The Safe & SuRe project team (Butler et al., 2016) proposed the global resilience analysis (GRA) that measures the response to various system failure modes instead of threats has been developed under and demonstrated in urban drainage

(Mugume et al., 2015) and water distribution (Diao et al., 2016) systems. Since system failures are more easily identifiable than threats, and all threats (known or unknown) that result in level of service failure will only do so if they also affect the system, this approach enables a more comprehensive analysis of resilience without the need for knowledge of unknowns. These studies revealed extreme system conditions to specific failures, e.g. the complete loss of water supply with only 5% pipe failure or still meeting 80% of demand despite over 70% of pipes failing (Diao et al 2016), and hence provide insights in developing proper interventions to improve WDS resilience. Some other studies contributed valuable insights on recovery strategies from different perspective, e.g. from preventing cascade failure (Shuang et al. 2017) and economic consequences (Lee et al. 2017), respectively.

Despite the studies above explored possible interventions to improve resilience of real-world case study systems, how to develop optimal interventions is still an open question, especially the optimal recovery strategy from extreme events featured with enormous failures. As rapid recovery with negative impact maximized is extremely important, this paper aims at exploring this issue via studying on the problem defined in the Battle of Post-Disaster Response and Restoration (BPDRR). Briefly, the problem is to identify the optimal recovery strategy of a real-world WDS (named as B-City) by scheduling three teams to repair or replace damaged pipes after an earthquake. Traditionally, researches mainly focus on hydraulic modelling-based detection of damaged (leaking) pipes in WDSs (Skworcow and Ulanicki 2011; Jung et al 2013). Hence, this study, which investigates the optimal strategy to fix the damaged pipes after detection, is an essential complimentary work to current researches. In this regard, the authors proposed a multi-phase optimization method in combination with manual intervention, which takes the advantage of evolutionary computation as well as engineering experiences.

PRELIMINARY ANALYSIS

For this version of the battle competition, five scenarios of likely damages after an earthquake have been selected based on the seismic conditions of B-city. The purpose of the BPDRR is to provide the water utility with a strategy on how to prioritize the use of its available resources to improve their capacity of restoring the service rapidly in handling such scenarios. A preliminary analysis of the system and the requirements of water utility was performed as outlined below:

(1) Type of damages - two types of damages are considered in this battle, namely, visible damages and nonvisible damages. Each damage is divided into breaks and leaks according to the damage severity. All breaks in pipes with diameter higher or equal to 150mm and all leaks in pipes with diameter higher or equal to 300mm are visible immediately after the earthquake. Also, if a break or a leak in any pipe reaches an outflow higher than 2.5L/s, it is considered to become visible. Visible damages are prioritized for restoration. The nonvisible damages are become visible only 48 hours after the event. The visible damages for each scenario that the crews are dispatched to begin the restoration is provided in Annex A.

(2) Damage restoration - a pipe with breaks need to perform three operating procedures, namely, isolation, replacement and reopen. While for a pipe with leaks, only two procedures (reparation and reopen) are required, there is no need to isolate the pipe

during a repair, although the pipe will continue leaking until the repair is finished. For each scenario, the times of replace replacement and repair replacement are calculated using the equations $0.233 \cdot D^{0.577}$ and $0.156 \cdot D^{0.719}$. The time for isolating a break pipe accounts for the sum of the time spent in closing the necessary valves, and its duration is equal to 15mins $\times$ number of valves to be closed (Annex B). The reopening of closed valves have zero duration.

SOLUTION METHOD FORMULATIONS

The B-City problem requires taking a large number of variables into account. The general idea behind the evolutionary computation and manual intervention was to increase the possibilities of identifying better solutions for such a challenging problem. As shown in Figure 1, we proposed a multi-phase optimization process in combination with manual intervention, which takes the advantage of evolutionary computation as well as engineering experiences. The method consists of three parts: (1) preliminary analysis; (2) sub-optimization; and (3) global optimization.

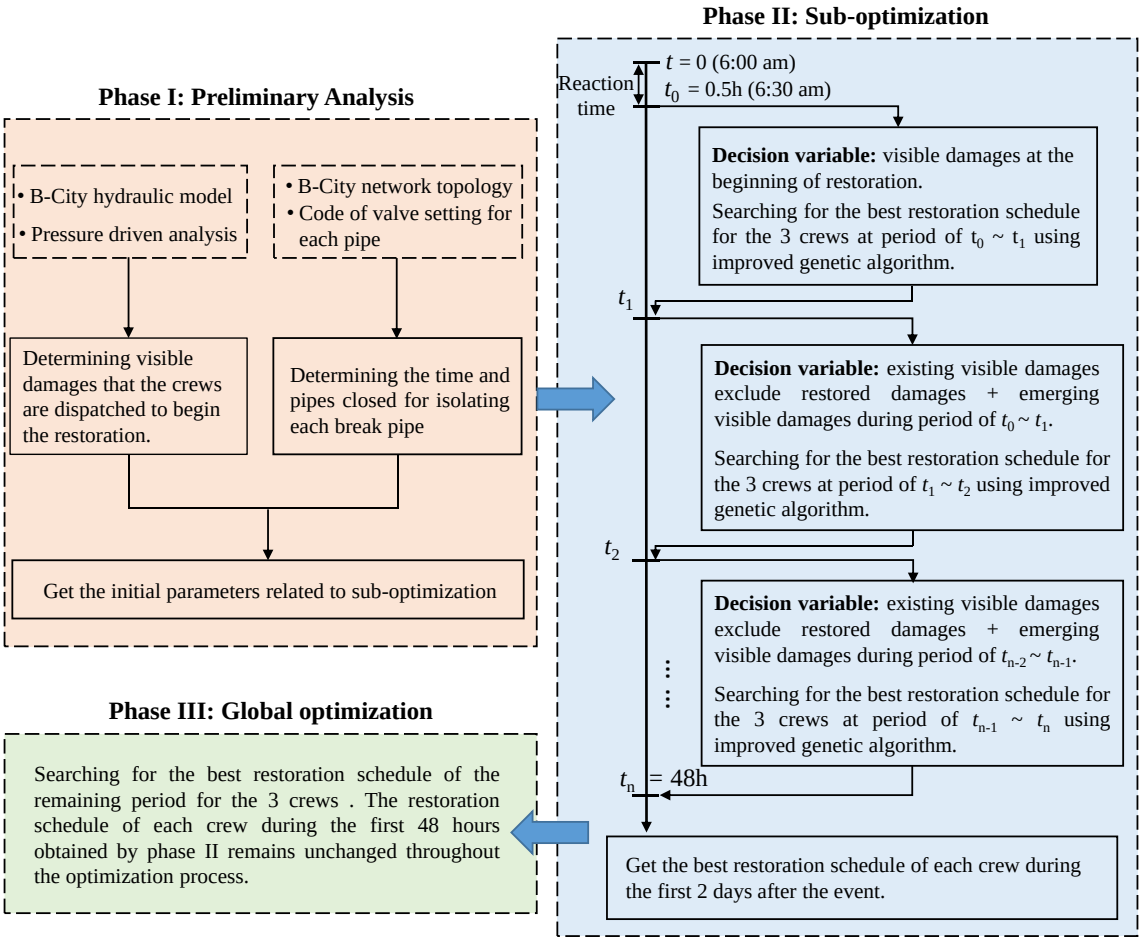

Fig. 1. Flowchart of Proposed Method

During the initial phase, some parameters related to sub-optimization need to be determined by preliminary analysis. These parameters include the time each crew takes to isolate each break pipe, the pipes closed for isolating each break pipe, and the visible

damages that the crews are dispatched to begin the restoration. Then, the problem is solved in two phases using improved genetic algorithm (IGA).

During the first 48 hours, a nonvisible break or leak in any pipe will become visible (outflow ≥ 2.5L/s) if the status of damaged pipes updated once they are isolated, repaired, replaced or reopened. This have highlighted the difficulties in solving the optimization problem due to its variable decision variables. Therefore, we proposed a time-phased optimization method (phase II in Figure 1) to overcome this difficulty. For each time period such as t_1 - t_2, the IGA was used to search the best restoration schedule for the 3 crews from the existing visible damages exclude restored damages and the emerging visible damages during previous period such as $t_0 \sim t_1$. Finally, we can get the best restoration schedule of each crew during the first 2 days after the event.

Due to the fact that the nonvisible damages are become visible only 2 days (48hrs) after the event, this also means that the number of decision variables does not change after 48 hours. Therefore, the problem is regarded as a standard optimization problem and list all the decision variables (except the restored damages during the first 2 days). In this case, we first fix the restoration schedule for the first 48 hours, and then searching the best restoration schedule of the remaining period for the 3 crews with the aid of IGA. Finally, we get the overall restoration schedule that can effectively help the water utility to respond to the disaster and restore the service rapidly.

OPTIMIZATION FRAMEWORK FOR BPDRR

As mentioned above, searching the best restoration schedule is a discrete nonlinear combinatory optimization problem. In this paper, six objective functions are formulated by taking into account (1) the recovery time for critical facilities and systems, (2) resilience loss, (3) the affected level of consumers, and (4) the volume of water lost. The optimization model is generalized as:

Search for: $\vec{X} = (P_i, K_i)$; $P_i \in D$; $i = 1, \ldots, N$

Minimize: $F(\vec{X})$

Where P_i = pipe index for visible damage i (breaks and leaks); K_i = type of operation in the process of restoration for visible damage i ; D = set of visible damages; N = number of visible damages; and $F(\vec{X})$ = objective function.

The decision variable is represented as a number of damage pipes with type of operation (isolation, replacement and reparation). Two variables are used for one damage pipe, namely a pipe index and a type of operation for the damage pipe. In this battle, the reopen operation immediate execution once the damage pipe is replaced according to our engineering experience, therefore each pipe with broken is assigned to two types (isolation and replacement). In addition, there is no need to isolate a leakage pipe in order to provide consumers with as much water or pressure as possible. The leakage pipe only requires reparation, although the pipe will continue leaking until the repair is finished. To sum up, there are $2 \times N_{break} + N_{leak}$ (N_{break} and N_{leak} are the number visible breaks and leaks, respectively) variables in proposed optimization model. To search for a

restoration schedule for the N visible damages, $2\times N_{break}+N_{leak}$ variables are required for being coded as one GA solution individual.

In this battle, we set different weights for each objective (criterion), so the six criteria are merged into a single optimization problem. This is followed by the optimization of restoration schedule for each scenario, respectively. Finally, the results are weighted sum to calculate the performance of the solution in the 5 damage scenarios for each criterion.

The proposed optimization framework was used to identify the best restoration schedule in Phase II and phase III. Considering the safety of life and property of residents, the 2 hospitals and 2 firefighting flows are a priority for restoring service in Phase II, so we first set the weight of criterion C_01 to 1.0 and the weight of the remaining criteria to 0 to search for the optimal schedule on the premise of restoring the 4 facilities as soon as possible. Once the scheme is determined, we fixed the scheme of current period (time from begin the restoration until full recovery of the 4 facilities) unchanged, then set the weight of criterion C_01 to 0 and the remaining 5 criteria (C_02 ~ C_06) are respectively set to 0.15, 0.15, 0.2, 0.4 and 0.1 to search for the best restoration schedule of the remaining period (time from full recovery of the 4 facilities until end of phase II). In phase III, the weight coefficients for the six criteria are also respectively set to 0, 0.15, 0.15, 0.2, 0.4 and 0.1 based on engineering experience to search for the optimal schedule of the remaining period (time from 48h until all the damages are fixed).

ALGORITHM FOR OPTIMIZATION

Genetic algorithms (GA) are population based search algorithms to solve combinatorial optimization problems proposed by Holland (1992). They generate solutions for optimization problem based on theory of evolution using concepts such as reproduction, crossover and mutation. The fundamental concept of a genetic algorithm states a set of conditions to achieve global optima. These conditions describe the reproduction process and ensure that better solution remain in future generations and weaker solutions be eliminated from future generations. This is similar to the Darwin's survival of fittest concept in the theory of evolution. In this battle, we modified the basic genetic algorithm and proposed an improved genetic algorithm (IGA) to solve the BPDRR more efficiently. The IGA search mechanism consists of three phases: (1) Evaluation of fitness function of each solution in the population, (2) selection of parent solutions based on fitness values, and (3) application of genetic operations such as crossover and mutation to generate new offspring.

Initial population

The initial population in genetic algorithm is normally generated randomly. For this battle, it should be noted that it must first be isolated before replace a broken pipe, namely, the order of "isolation" needs to precede "replacement" for a broken pipe. A simple visible damages contains 3breaks and 2leaks is used to illustrate the process of initializing the population. There are 8 ($2\times3+2$) variables in an individual given as follows:

Serial number	①	②	③	④	⑤	⑥	⑦	⑧
Pipe ID	58	58	618	618	630	630	380	3895

Activity	isolate	replace	isolate	replace	isolate	replace	repair	repair
Variable	(1, 1)	(1, 2)	(2, 1)	(2, 2)	(3, 1)	(3, 2)	(4, 3)	(5, 3)

The operation of isolation, replacement and reparation are encoded as 1, 2 and 3, respectively. Where (1,1) indicates that "isolation" is executed for the pipe with index number 1. On the premise of satisfying the constraint, the population of a given number of individuals can be generated by arranging the serial numbers randomly. For example, two individuals randomly generated are as follows:

Parent 1	③	④	⑧	①	⑦	②	⑤	⑥
Parent 2	③	①	②	⑤	⑥	⑧	④	⑦

Evaluation

The superiority of individuals within the population needs to be determined by evaluating the fitness value of each individual. The chromosomes need to be decoded before they are evaluated. Take the example of parent 1 in the initial population, the isolation time of pipe58, pipe618 and pipe630 are 30, 15 and 30 minutes, respectively. Similarly, the replacement time for these pipes are both 180 minutes. Pipe380 and Pipe 3895 both had the same repair time, that is, both 240 minutes. In this battle, assume that the operation of "isolation" and "replacement" for one break pipe can only be performed by one engineering team. The decoded chromosomes for parent 1 are shown below.

CREW 01			
Pipe ID	Activity	Start time	End time
618	isolate	6:30	6:45
618	replace	6:45	9:45
630	isolate	9:45	10:15
630	replace	10:15	13:15
CREW 02			
3895	repair	6:30	10:30
CREW 03			
58	isolate	6:30	7:00
380	repair	7:00	11:00
58	replace	11:00	14:00

Then, the decoded chromosomes are used to calculate the fitness for each individual with the aid of hydraulic simulation which have a total duration of 7 days with a time step of 15 minutes and is performed considering the mentioned pressure driven demands. For each time step, the status of the crews is checked from the schedules and the required pipe isolations is included in the model. The status of the pipes will also be updated once they are isolated (closing the pipe), repaired or replaced (removing the emitter flow), or reopened (opening the pipes). Once the hydraulic response of the system is computed, the fitness for each individual will be calculated using the results.

Crossover operator

Since the BPDRR is a discrete combinatory optimization problem and the classical crossover operators such as one-point, two-point, and uniform crossovers are not suitable. Figure 2 illustrates the failure of two-point crossover for the BPDRR. Therefore, we

choose Partially mapped crossover (PMX) operator to address the issue. PMX (Goldberg and Lingle, 1985) is one of the most popular and effective crossovers for order-based GAs to deal with combinatorial optimization problems. In view of the operation, PMX can be regarded as a modification of two-point crossover but additionally uses a mapping relationship to legalize offspring that have duplicate numbers. The algorithm of PMX is given bellow:

1. **Substring selection:** Cut each parent into two substrings, and then select one substring for each parent at random.
2. **Substring exchange:** Exchange the two selected substrings to produce proto-offspring.
3. **Mapping list determination:** Determine the mapping relationship based on the selected substrings.
4. **Offspring legalization:** Legalize proto-offspring with the mapping relationship.

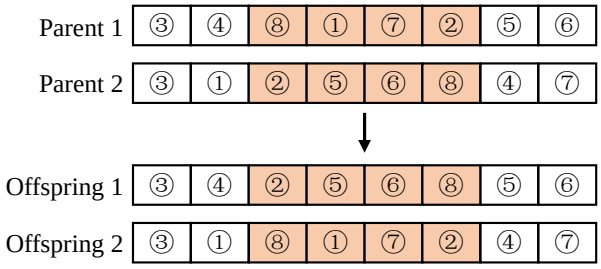

Figure 2. Failure of two-point crossover

Figure 3 illustrates how PMX legalizes the offspring in Figure 2. Assume that the selected substrings in Step 1 are [⑧ ① ⑦ ②] for Parent 1 and [② ⑤ ⑥ ⑧] for Parent 2. These two substrings are then exchanged to produce proto-offspring in Step 2. Note that the proto-offspring are possibly illegal. Steps 3 and 4 in PMX then fix the illegal offspring. In Step 3, the mapping relationship is established according to the selected substrings, e.g., '②' to '⑧', '⑤' to '①', and '⑥' to '⑦' in Fig. 2. To legalize the proto-offspring, the fourth step of PMX replaces the duplicates genes with the corresponding genes in the mapping relationship.

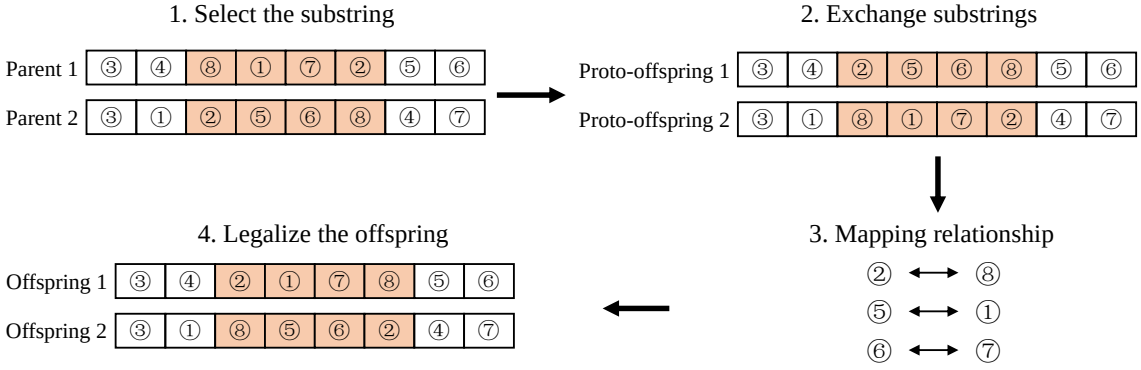

Figure 3. Example of PMX

Finally, it needs to check whether the offspring generated using PMX operator satisfy the constraint, that is the order of "isolation" needs to precede "replacement" for a broken pipe. As shown in Figure 3, the variable '②' and '①' are in violation of constraint because the pipe with index number 1 is replaced before it is isolated. The conflict can be resolved by swapping the order of '②' and '①'.

Mutation

Mutation is another important operator in GAs. This operator changes a small amount of genes to activate the population diversity. Several mutation operators have been proposed for order based GAs. This battle adopts the well-known swap mutation (Syswerda, 1991), which swaps genes at two randomly chosen loci. The offspring generated through mutation is also need to check the order of operations for each breaks and swap the two operation sequences for a break that is in violation of constraint.

Elitist selection

Selection is the stage of a genetic algorithm in which individual genomes are chosen from a population for later breeding (using the crossover operator). In this battle, in order to prevent the random destruction by crossover or mutation operators of individuals with good genetics, we use elitist selection (Rudolph 1994) to overcome this shortcoming. Elitist selection is a selection strategy where a limited number of individuals with the best fitness values are chosen to pass to the next generation, avoiding the crossover and mutation operators. The number of elite individuals should not be too high, otherwise the population will tend to degenerate. The number of elite individuals was set to 10 in this battle.

RESULTS

Using the methodology described above, we have got the final solution with a balance on six objectives and the detail restoration schedule of the 3 crews for each scenario was provided in Annex C. The change of evaluation index with time step for each scenario is provided in Annex D. A summary of solutions for BPDRR was summarized as follows.

Table 1. Summary of Solutions for B-City Post-Disaster Response and Restauration

Criteria	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Total	Unit
C_01	675.00	0.00	195.00	405.00	0.00	146.9801	[mins]
C_02	3675.00	2205.00	3705.00	3645.00	3645.00	3161.312	[mins]
C_03	25894.00	4329.00	12044.00	12893.00	9323.00	10236.54	[%*min]
C_04	184.29	44.61	55.02	87.53	67.17	75.95749	[mins]
C_05	103.00	8.00	9.00	25.00	27.00	28.62555	[ ]
C_06	77276935	49971497	79020416	69567629	58761590	60380393	[L]

In view of the safety of the lives and property of the residents, we have given priority to ensuring that the four key facilities are restored to their water supply capacity as soon as possible. As shown in Figure D1(A) ~ Figure D4(A), the four key facilities are fully restored their water supply capacity within 29, 10.5, and 11 hours after the disaster for scenario 1, scenario 3 and scenario 4, respectively. Especially for scenario 2 and 5, these four key facilities met the water supply requirement during the entire simulation period. As shown in Table 1, the time that the hospitals and the firefighting flows are without supply for the 5 scenarios are 675, 0, 195, 405 and 0 minutes, respectively.

Following the restoration of water supply capacity at these four key facilities, we focused on the remaining criteria, especially for the number of nodes without service for more than eight consecutive hours due to its significant impact on local residents' lives. As shown in Table 1, the number of nodes without service for more than 8 consecutive hours for the 5 scenarios are 103, 8, 9, 25 and 27 respectively. Compared to the total number of nodes (i.e. 4201), the optimal solution has brought the number to an acceptable level.

The last criterion C_06 was not taken seriously throughout the restoration process. This is because the water utility may care less about the volume of water lost during the next 7 days after the event, which caused a higher value of C_06 (Table 1).

ALTERNATIVES TO IMPROVE THE CAPACITY

In order to provide effective suggestions to the water utility, a sensitivity analysis is needed to mining useful information hidden in the optimal results. The impact on water supply capacity of the critical facilities and systems after each visible break at the beginning of restoration is respectively isolated for each scenario are shown in Figure 4. For scenario 1 in Figure 4, isolate breaks 437, 5837 and 5698 will have a greater impact on the system and critical facilities. As shown in Figure 4, isolating pipe 437 at the period of 10:00am ~ 22:00pm will affect water supply at critical facilities, as a result, the pipe will need to be isolated and replaced after 22:00 pm. Similarly, broken pipe 5698 should be isolated and replaced after 12:00pm to avoid negative impacts on water supply to critical facilities. These can be confirmed by the optimal results (Annex C). The remaining scenarios were analyzed in a similar way.

With the aid of the proposed optimization framework and sensitivity analysis, we have the following proposals to improve the current capacity of restoring the service rapidly after the event:

1. First identify the pipes that affect the water supply capacity at the four critical facilities based on sensitivity analysis for the visible breaks at the beginning of restoration.
2. Search for the optimal schedule according to the visible breaks identified by step 1 to ensure the four critical facilities are restored as soon as possible.
3. After, the number of nodes without service for more than eight consecutive hours should be minimized via the optimal scheduling
4. Once the scheme for the above two steps are determined, then search for the optimal schedule of the remaining period using the proposed optimization method.

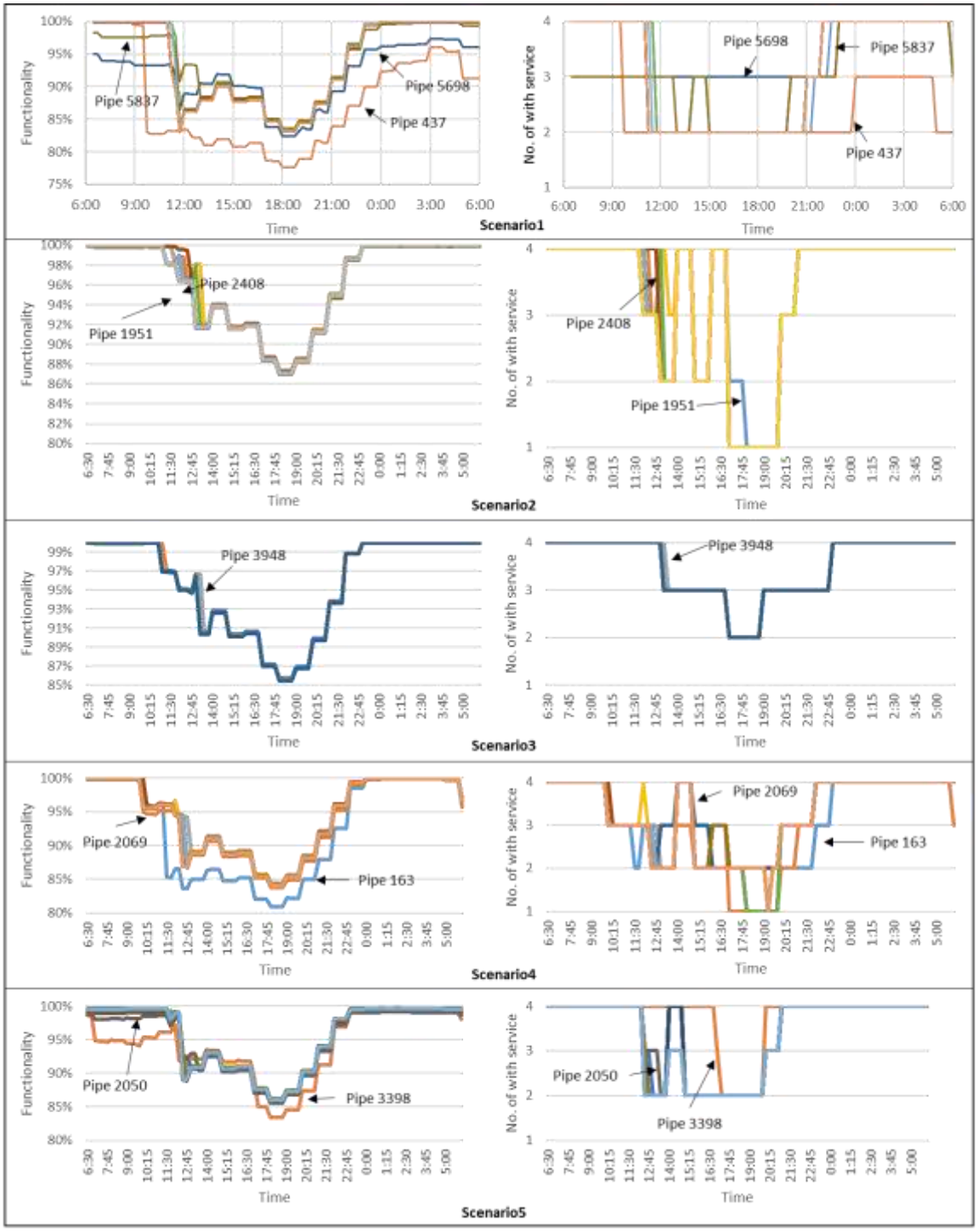

Figure 4. Impact on water supply capacity of the critical facilities and systems after each visible break at the beginning of restoration is respectively isolated for each scenario.

DISCUSSIONS

Improving resilience in water infrastructure is a crucial step towards more sustainable urban water management. The resilience mentioned here certainly requires a water

infrastructure can rapidly recover from any failure conditions and meanwhile minimize the magnitude and duration of negative impacts.

Since resilience research in water distribution networks is at a early stage, most of studies focuses on developing methodologies for resilience evaluation rather than developing optimal recovery interventions. Accordingly, this study explores this issue via studying on the problem defined in the Battle of Post-Disaster Response and Restoration (BPDRR). Briefly, the problem is to identify the optimal recovery strategy of a real-world WDS (named as B-City) by scheduling three teams to repair or replace damaged pipes after an earthquake. We proposed a multi-phase optimization method in combination with manual intervention, which takes the advantage of evolutionary computation as well as engineering experiences.

The results provide some value insights on how to make considerate optimal recovery plan. For instance, certain broken pipes have to be fixed between particular time stamps to avoid negative effects on the level of services at some critical facilities

REFERENCES

Berardi, L., R. Ugarelli, J. Røstum, and O. Giustolisi (2014). "Assessing mechanical vulnerability in water distribution networks under multiple failures". *Water Resour. Res.*, 50, 2586–2599, doi:10.1002/2013WR014770.

Bristow, E., Brumbelow, K., and Kanta, L. (2007). "Vulnerability Assessment and Mitigation Methods for Interdependent Water Distribution and Urban Fire Response Systems". *World Environmental and Water Resources Congress*, pp. 1–10.

Cimellaro, G.P., Tinebra, A., Renschler, C. and Fragiadakis, M. (2016). "New Resilience Index for Urban Water Distribution Networks", *Journal of Structural Engineering*, Vol 142, Issue 8, C4015014.

D. Butler *et al.*, "Reliable, resilient and sustainable water management: the Safe & SuRe approach," *Global Challenges, doi: 10.1002/gch2.1010.*, 2016.

D Jung , D Kang, J Liu, K Lansey (2013). "Improving Resilience of Water Distribution System through Burst Detection", World Environmental & Water Resources Congress , 2013, pp. 768-776.

Gheisi, A. and Naser, G. (2014). "Water distribution system reliability under simultaneous multicomponent failure scenario". Journal - American Water Works Association, 106(7), E319-E326.

Goldberg, D. E., & Lingle, R. (1985). Alleles, loci, and the traveling salesman problem. In *Proceedings of an international conference on genetic algorithms and their applications*, 7(154), 154-159.

Holland, J. H. (1992). Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence. *MIT press*.

K. A. Klise, M. Bynum, D. Moriarty and R. Murray. (2017). “A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study”, *Environmental Modelling and Software*, 95, pp. 420-431.

Kanta, L. and Brumbelow, K. (2013).”Vulnerability, Risk, and Mitigation Assessment of Water Distribution Systems for Insufficient Fire Flows.” J. Water Resour. Plann.Manage., 139(6), 593–603.

Kanta, L (2006). Vulnerability Assessment of Water Supply Systems For Insufficient Fire Flows. Master thesis, Texas A&M University.

K. Diao, C. Sweetapple, R. Farmani, G. Fu, S. Ward, and D. Butler, "Global Resilience Analysis of Water Distribution Systems," Water Research, vol. 106, pp. 383-393, 2016.

LF Gay, SK Sinha. (2014). “Stochastic simulation methodology for resilience assessment of water distribution networks”, International Journal of Critical Infrastructure, Vol 10 Issue 2, pp. 134-150.

Mugume, S.N., Gomez, D.E., Fu, G., Farmani, R, Butler, D. (2015). A global analysis approach for investigating structural resilience in urban drainage systems, *Water Research*, 10.1016/j.watres.2015.05.030.

O Piller et al. (2017). “Augmented Resilience of Water Distribution Systems following Severe Abnormal Events”, CCWI2017– Computing and Control for the Water Industry, Sheffield 5th - 7th September 2017.

Pandit, A and Crittenden, C. (2016). “Index of network resilience for urban water distribution systems”, *International Journal of Critical Infrastructures*, vol 12, Issue 1/2, pp120-142.

P Skworcow , B Ulanicki. (2011). “Burst Detection in Water Distribution Systems via Active Identification Procedure”. *Human Reproduction*, 2011 , Vol 22, Issue 1, pp. 101-8.

Rudolph, G. (1994). Convergence analysis of canonical genetic algorithms. *IEEE transactions on neural networks*, 5(1), 96-101.

Shuang, Q., Yuan, Y., Zhang, M. and Liu, Y. (2017). “A Cascade-Based Emergency Model for Water Distribution Network”, *Mathematical Problems in Engineering*, Vol 2015, http://dx.doi.org/10.1155/2015/827816

S Lee, S Shin, D Judi, T Mcpherson and S Burian (2017). “Water Distribution System Recovery Strategies Considering Economic Consequences from Business Loss”, CCWI2017– Computing and Control for the Water Industry, Sheffield 5th - 7th September 2017.

S. Shin et al. (2018). “A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems”, *Water*, 10, 164; doi:10.3390/w10020164.

Syswerda, G. (1991). Schedule optimization using genetic algorithms. In L. Davis (Ed.), *Handbook of genetic algorithms*, 332–349.

Yazdani, A.; Otoo, R.A.; Jeffrey, P. (2011). “Resilience enhancing expansion strategies for water distribution systems: A network theory approach”. *Environ. Model. Softw.*, 26, 1574–1582.

Annex A

Table A1 Visible damages at the beginning of restoration for scenario 1

Damages	Pipe ID
Breaks	437,3602,2112,3562,5333,5698,3045,338,5837,3391,254,4661,1413
Leaks	4805,3342,3772,3571,5066,5869,6065,1060,1702,2704,3124,3404,3640,3693,380,3895,4082,5135,6005,620,776,3884,1763,280,3273,3387,3446,3545,3572,3817,3969,4050,450,610,616

Table A2 Visible damages at the beginning of restoration for scenario 2

Damages	Pipe ID
Breaks	1951,3414,4988,5251,3404,6005,1252,2408,3094,3293,1186,288,3564,6023,5775
Leaks	4409,163,2881,5871,2094,2141,3449,2001,2910,3679,3875,4035,4038,4246,4788,1105,2307,2409,2726,2821,2983,3760,4062,4083,5691,762

Table A3 Visible damages at the beginning of restoration for scenario 3

Damages	Pipe ID
Breaks	716,3948,92,3435,3979,1972,282
Leaks	168,770,3658,140,2252,3399,3903,4899,5456,3414,1004,1384,1922,2604,3264,3380,341,3804,3836,338,1788,1902,2263,2825,2904,2913,3019,3032,3402,3403,5125,5865,2315,2554,2695,2710,2792,3082,5198,5783,5983,682,771,798,994

Table A4 Visible damages at the beginning of restoration for scenario 4

Damages	Pipe ID
Breaks	163,2069,5942,3557,1558,3693,1813,1844,245,610,2269,2721,3758,1162
Leaks	4805,2,5344,2844,4139,5995,791,2897,3571,1869,3123,1612,3679,3045,1966,1425,2145,3488,3624,3634,5362,5988,6016,699,788,816,5198,1341,1414,2137,2992,3433,5357

Table A5 Visible damages at the beginning of restoration for scenario 5

Damages	Pipe ID
Breaks	3922,3398,3825,4117,1902,3019,91,1540,2050,2115,378,4129,721
Leaks	4805,2068,2464,3754,5022,5194,1832,1926,335,3409,6012,809,5865,6005,1060,1936,1794,1558,1640,2626,3123,3547,3690,3723,5688,626,4316,4065,3121,3536,3613,3615,3800,3842,4093,838

Annex B

Table B1 The time and pipes closed for isolating each break pipe for scenario 1

Breaks ID	Pipes closed for isolation	Isolation time (min)	Breaks ID	Pipes closed for isolation	Isolation time (min)
437	169,623,4384	45	1379	1379	30
3602	3602	30	1413	1413,1435,1436	45
2112	2112,2123,2124,2106	60	1701	1701,1734,1733,1724	60
3562	3562,3584,3721,3270	60	1952	1952	30
5333	5332,5327,5384	45	2065	2066,2052,2134,2135,2132,2120	90
5698	5696,5695,5738,5824,5853,5841	90	3144	3144	30
3045	3045,3047,3046,2980	60	3187	3187,3198,3151	45
338	338	30	3681	3688,3794,3770,3668,3788,	75
5837	5837,5760,5838,5835	60	446	435,423	30
3391	3360,3438,3364,3439	60	4895	4895,4990,	30
254	285,287,286,248,256	75	58	66,67	30
4661	4692,4673,4656,4648	60	618	618	15
5105	5105	15	630	630	30
1221	1221	30			

Table B2 The time and pipes closed for isolating a break pipe for scenario 2

Breaks ID	Pipes closed for isolation	Isolation time (min)	Breaks ID	Pipes closed for isolation	Isolation time (min)
1951	1951,1948,1618	45	288	288	30
3414	3443,3359,3402,3280	60	3564	3564,3572,3466	45
4988	4988	30	6023	6023	30
5251	5251	30	2508	2508	15
3404	3404,3399,3401,3344	60	2535	2535,2536,2534	45
6005	6005,6027,6026	45	2543	2564,2563	30
1252	1252,1317,1346,1347	60	3104	3104	30
2408	2408,2435,2426	45	3125	3125,3112,3157,3174,3141,3137	90
3094	3094	30	4132	4136,4134,4133,4002,4098,4057,4010	105
3293	3294,3252,3287,3340,3339,3357,3285	105	4915	4916,4902,4878	45
1186	1186,1192,1244,1216	60	5775	5810,5751	30

Table B3 The time and pipes closed for isolating a break pipe for scenario 3

Breaks ID	Pipes closed for isolation	Isolation time (min)	Breaks ID	Pipes closed for isolation	Isolation time (min)
716	716	30	1588	1588,1589	30
3948	3948,3825,3868,3845	60	2116	2116	15
92	92,93,51,84	60	2140	2140	15
3435	3435	30	2318	2318,2326,2327	45
3979	3979	15	3714	3764,3716,3616,3711	60
1972	2043,1969,1971	45	4125	4125	15
282	282	30	4174	4174,4190,4192	45
1657	1657,1690,1625,1623	60	5144	5151,5145	30
3122	3133,3134,3111,3121	60	5604	5604	15
2999	2999	30	5946	5946,5968	30
1019	1019,1017	30			

Table B4 The time and pipes closed for isolating a break pipe for scenario 4

Breaks ID	Pipes closed for isolation	Isolation time (min)	Breaks ID	Pipes closed for isolation	Isolation time (min)
163	160,436	30	4624	4624,4625,4621	45
2069	2069,2064	30	2060	2060	15
5942	5942	30	1162	1162,1192,1183	45
3557	3556,3535,3663,3662,3537	75	1280	1280	30
1558	1559,1556,1554,1557	60	150	150	15
3693	3703,3707,3706,3692,3688,3674,3678	105	1618	1618	15
1813	1813	30	2062	2062	30
1844	1844,1941	30	2914	2914	30
245	245,250,249	45	4010	4010	30
610	610,629,620,603,556,574	90	5120	5129,5128	30
2269	2269,2268,2262,2265	60	5277	5315,5296	30
2721	2721	30	5287	5339,5288,5233,5334,5273	75
3758	3744,3621,3782,3655	60	842	842	30

Table B5 The time and pipes closed for isolating a break pipe for scenario 5

Breaks ID	Pipes closed for isolation	Isolation time (min)	Breaks ID	Pipes closed for isolation	Isolation time (min)
3922	3922	30	1402	1401	15
3398	3398,3395,3408,3388	60	4652	4652	15
3825	3825,3948,3868,3845	60	1282	1267	15
4117	4117,4077	30	1631	1631	30
1902	2006,1897	30	2404	2423,2405,2368	45
3019	2940,3165,3162,3161,3115,3075	90	246	279	15
91	89,p94	30	2804	2804,2821,2827,2796,2760,2712,2752	105
1540	1540	15	3136	3136,3101,3135,3095,3094,3130	90
2050	2050,2049,2005,1986,1975	75	3807	3807,3808,3802	45
2115	2115,2152	30	4748	4748	30
378	378,391	30	475	475	15
4129	4129	30	5004	4981	30
1028	1028,1081,1096	45	5458	5457,5436,5447,5566,5579,5596,5597,5474	120
4594	4595,4551	30	60	59,65,66	45
2162	2162	30	721	750,741,720,704	60
5105	5105	15			

Annex C

Table C1. The detail restoration schedule of the 3 crews for scenario 1

Crew 01							
Pipe ID	5869	Activity	repair	starttime:	1800	endtime:	16200
Pipe ID	6005	Activity	repair	starttime:	16200	endtime:	30600
Pipe ID	610	Activity	repair	starttime:	30600	endtime:	41400
Pipe ID	3404	Activity	repair	starttime:	41400	endtime:	55800
Pipe ID	616	Activity	repair	starttime:	55800	endtime:	66600
Pipe ID	3895	Activity	repair	starttime:	66600	endtime:	81000
Pipe ID	3571	Activity	repair	starttime:	81000	endtime:	95400
Pipe ID	6065	Activity	repair	starttime:	95400	endtime:	109800
Pipe ID	1060	Activity	repair	starttime:	109800	endtime:	124200
Pipe ID	450	Activity	repair	starttime:	124200	endtime:	135000
Pipe ID	3562	Activity	isolation	starttime:	135000	endtime:	138600
Pipe ID	4082	Activity	repair	starttime:	138600	endtime:	153000
Pipe ID	3446	Activity	repair	starttime:	153000	endtime:	163800
Pipe ID	380	Activity	repair	starttime:	163800	endtime:	178200
Pipe ID	3572	Activity	repair	starttime:	178200	endtime:	189000
Pipe ID	3342	Activity	repair	starttime:	189000	endtime:	207000
Pipe ID	3969	Activity	repair	starttime:	207000	endtime:	217800
Pipe ID	776	Activity	repair	starttime:	217800	endtime:	232200
Pipe ID	3693	Activity	repair	starttime:	232200	endtime:	246600
Pipe ID	3562	Activity	replacemant	starttime:	246600	endtime:	271800
Pipe ID	5105	Activity	isolation	starttime:	271800	endtime:	272700
Pipe ID	3144	Activity	isolation	starttime:	272700	endtime:	274500
Pipe ID	2065	Activity	isolation	starttime:	274500	endtime:	279900
Pipe ID	2065	Activity	replacemant	starttime:	279900	endtime:	290700
Pipe ID	3187	Activity	isolation	starttime:	290700	endtime:	293400
Pipe ID	605	Activity	repair	starttime:	293400	endtime:	300600
Pipe ID	3187	Activity	replacemant	starttime:	300600	endtime:	311400
Pipe ID	1593	Activity	repair	starttime:	311400	endtime:	318600
Pipe ID	940	Activity	repair	starttime:	318600	endtime:	325800
Pipe ID	1952	Activity	isolation	starttime:	325800	endtime:	327600
Pipe ID	630	Activity	isolation	starttime:	327600	endtime:	329400
Pipe ID	3834	Activity	repair	starttime:	329400	endtime:	336600
Pipe ID	3897	Activity	repair	starttime:	336600	endtime:	343800
Pipe ID	1176	Activity	repair	starttime:	343800	endtime:	351000
Pipe ID	2599	Activity	repair	starttime:	351000	endtime:	358200
Pipe ID	5793	Activity	repair	starttime:	358200	endtime:	365400
Pipe ID	5787	Activity	repair	starttime:	365400	endtime:	376200
Pipe ID	191	Activity	repair	starttime:	376200	endtime:	383400
Pipe ID	3285	Activity	repair	starttime:	383400	endtime:	390600
Pipe ID	446	Activity	isolation	starttime:	390600	endtime:	392400

Pipe ID	446	Activity	replacemant	starttime:	392400	endtime:	403200
Pipe ID	3257	Activity	repair	starttime:	403200	endtime:	410400
Pipe ID	1595	Activity	repair	starttime:	410400	endtime:	417600
Pipe ID	38	Activity	repair	starttime:	417600	endtime:	424800
Pipe ID	5105	Activity	replacemant	starttime:	424800	endtime:	435600
Pipe ID	5933	Activity	repair	starttime:	435600	endtime:	446400
Pipe ID	3147	Activity	repair	starttime:	446400	endtime:	453600
Pipe ID	3144	Activity	replacemant	starttime:	453600	endtime:	464400
Pipe ID	1952	Activity	replacemant	starttime:	464400	endtime:	475200
Pipe ID	5023	Activity	repair	starttime:	475200	endtime:	482400
Pipe ID	630	Activity	replacemant	starttime:	482400	endtime:	493200
Crew 02							
Pipe ID	3273	Activity	repair	starttime:	1800	endtime:	12600
Pipe ID	5066	Activity	repair	starttime:	12600	endtime:	27000
Pipe ID	5333	Activity	isolation	starttime:	27000	endtime:	29700
Pipe ID	3884	Activity	repair	starttime:	29700	endtime:	40500
Pipe ID	1413	Activity	isolation	starttime:	40500	endtime:	43200
Pipe ID	280	Activity	repair	starttime:	43200	endtime:	54000
Pipe ID	5135	Activity	repair	starttime:	54000	endtime:	68400
Pipe ID	3640	Activity	repair	starttime:	68400	endtime:	82800
Pipe ID	3045	Activity	isolation	starttime:	82800	endtime:	86400
Pipe ID	5333	Activity	replacemant	starttime:	86400	endtime:	111600
Pipe ID	338	Activity	isolation	starttime:	111600	endtime:	113400
Pipe ID	3124	Activity	repair	starttime:	113400	endtime:	127800
Pipe ID	620	Activity	repair	starttime:	127800	endtime:	142200
Pipe ID	5837	Activity	isolation	starttime:	142200	endtime:	145800
Pipe ID	1702	Activity	repair	starttime:	145800	endtime:	160200
Pipe ID	1763	Activity	repair	starttime:	160200	endtime:	171000
Pipe ID	1413	Activity	replacemant	starttime:	171000	endtime:	181800
Pipe ID	5837	Activity	replacemant	starttime:	181800	endtime:	199800
Pipe ID	2704	Activity	repair	starttime:	199800	endtime:	214200
Pipe ID	3045	Activity	replacemant	starttime:	214200	endtime:	232200
Pipe ID	338	Activity	replacemant	starttime:	232200	endtime:	250200
Pipe ID	4369	Activity	repair	starttime:	250200	endtime:	257400
Pipe ID	618	Activity	isolation	starttime:	257400	endtime:	258300
Pipe ID	3331	Activity	repair	starttime:	258300	endtime:	265500
Pipe ID	47	Activity	repair	starttime:	265500	endtime:	272700
Pipe ID	4652	Activity	repair	starttime:	272700	endtime:	279900
Pipe ID	5062	Activity	repair	starttime:	279900	endtime:	287100
Pipe ID	614	Activity	repair	starttime:	287100	endtime:	294300
Pipe ID	3038	Activity	repair	starttime:	294300	endtime:	301500
Pipe ID	2597	Activity	repair	starttime:	301500	endtime:	308700
Pipe ID	2999	Activity	repair	starttime:	308700	endtime:	315900

Pipe ID	4889	Activity	repair	starttime:	315900	endtime:	323100
Pipe ID	1978	Activity	repair	starttime:	323100	endtime:	330300
Pipe ID	740	Activity	repair	starttime:	330300	endtime:	337500
Pipe ID	1379	Activity	isolation	starttime:	337500	endtime:	339300
Pipe ID	1175	Activity	repair	starttime:	339300	endtime:	346500
Pipe ID	902	Activity	repair	starttime:	346500	endtime:	353700
Pipe ID	4757	Activity	repair	starttime:	353700	endtime:	360900
Pipe ID	3681	Activity	isolation	starttime:	360900	endtime:	365400
Pipe ID	1221	Activity	isolation	starttime:	365400	endtime:	367200
Pipe ID	3681	Activity	replacemant	starttime:	367200	endtime:	378000
Pipe ID	1892	Activity	repair	starttime:	378000	endtime:	385200
Pipe ID	618	Activity	replacemant	starttime:	385200	endtime:	396000
Pipe ID	1221	Activity	replacemant	starttime:	396000	endtime:	406800
Pipe ID	2705	Activity	repair	starttime:	406800	endtime:	414000
Pipe ID	3950	Activity	repair	starttime:	414000	endtime:	421200
Pipe ID	363	Activity	repair	starttime:	421200	endtime:	432000
Pipe ID	3497	Activity	repair	starttime:	432000	endtime:	439200
Pipe ID	1241	Activity	repair	starttime:	439200	endtime:	446400
Pipe ID	4505	Activity	repair	starttime:	446400	endtime:	453600
Pipe ID	1379	Activity	replacemant	starttime:	453600	endtime:	464400
Pipe ID	5577	Activity	repair	starttime:	464400	endtime:	471600
Pipe ID	210	Activity	repair	starttime:	471600	endtime:	478800
Crew 03							
Pipe ID	4805	Activity	repair	starttime:	1800	endtime:	23400
Pipe ID	5698	Activity	isolation	starttime:	23400	endtime:	28800
Pipe ID	3391	Activity	isolation	starttime:	28800	endtime:	32400
Pipe ID	3391	Activity	replacemant	starttime:	32400	endtime:	46800
Pipe ID	4661	Activity	isolation	starttime:	46800	endtime:	50400
Pipe ID	2112	Activity	isolation	starttime:	50400	endtime:	54000
Pipe ID	3602	Activity	isolation	starttime:	54000	endtime:	55800
Pipe ID	437	Activity	isolation	starttime:	55800	endtime:	58500
Pipe ID	437	Activity	replacemant	starttime:	58500	endtime:	105300
Pipe ID	4661	Activity	replacemant	starttime:	105300	endtime:	119700
Pipe ID	3602	Activity	replacemant	starttime:	119700	endtime:	144900
Pipe ID	3545	Activity	repair	starttime:	144900	endtime:	155700
Pipe ID	4050	Activity	repair	starttime:	155700	endtime:	166500
Pipe ID	5698	Activity	replacemant	starttime:	166500	endtime:	191700
Pipe ID	3772	Activity	repair	starttime:	191700	endtime:	209700
Pipe ID	3817	Activity	repair	starttime:	209700	endtime:	220500
Pipe ID	254	Activity	isolation	starttime:	220500	endtime:	225000
Pipe ID	254	Activity	replacemant	starttime:	225000	endtime:	239400
Pipe ID	3387	Activity	repair	starttime:	239400	endtime:	250200
Pipe ID	2112	Activity	replacemant	starttime:	250200	endtime:	275400

Pipe ID	5497	Activity	repair	starttime:	275400	endtime:	286200
Pipe ID	880	Activity	repair	starttime:	286200	endtime:	293400
Pipe ID	517	Activity	repair	starttime:	293400	endtime:	300600
Pipe ID	4518	Activity	repair	starttime:	300600	endtime:	307800
Pipe ID	58	Activity	isolation	starttime:	307800	endtime:	309600
Pipe ID	5436	Activity	repair	starttime:	309600	endtime:	316800
Pipe ID	1701	Activity	isolation	starttime:	316800	endtime:	320400
Pipe ID	58	Activity	replacemant	starttime:	320400	endtime:	331200
Pipe ID	1701	Activity	replacemant	starttime:	331200	endtime:	342000
Pipe ID	32	Activity	repair	starttime:	342000	endtime:	349200
Pipe ID	5067	Activity	repair	starttime:	349200	endtime:	356400
Pipe ID	4895	Activity	isolation	starttime:	356400	endtime:	358200
Pipe ID	4895	Activity	replacemant	starttime:	358200	endtime:	369000
Pipe ID	5203	Activity	repair	starttime:	369000	endtime:	376200
Pipe ID	1818	Activity	repair	starttime:	376200	endtime:	383400
Pipe ID	5920	Activity	repair	starttime:	383400	endtime:	390600
Pipe ID	1969	Activity	repair	starttime:	390600	endtime:	401400
Pipe ID	840	Activity	repair	starttime:	401400	endtime:	408600
Pipe ID	69	Activity	repair	starttime:	408600	endtime:	415800
Pipe ID	4880	Activity	repair	starttime:	415800	endtime:	423000
Pipe ID	3101	Activity	repair	starttime:	423000	endtime:	430200
Pipe ID	5453	Activity	repair	starttime:	430200	endtime:	437400
Pipe ID	4594	Activity	repair	starttime:	437400	endtime:	444600
Pipe ID	4319	Activity	repair	starttime:	444600	endtime:	451800
Pipe ID	1369	Activity	repair	starttime:	451800	endtime:	459000
Pipe ID	5188	Activity	repair	starttime:	459000	endtime:	466200
Pipe ID	2298	Activity	repair	starttime:	466200	endtime:	477000
Pipe ID	3854	Activity	repair	starttime:	477000	endtime:	484200

Table C2. The detail restoration schedule of the 3 crews for scenario 2

Crew 01							
pipe ID	4988	Activity	isolation	starttime:	1800	endtime:	3600
pipe ID	3094	Activity	isolation	starttime:	3600	endtime:	5400
pipe ID	1951	Activity	isolation	starttime:	5400	endtime:	8100
pipe ID	6023	Activity	isolation	starttime:	8100	endtime:	9900
pipe ID	288	Activity	isolation	starttime:	9900	endtime:	11700
pipe ID	3293	Activity	isolation	starttime:	11700	endtime:	18000
pipe ID	3414	Activity	isolation	starttime:	18000	endtime:	21600
pipe ID	5251	Activity	isolation	starttime:	21600	endtime:	23400
pipe ID	3293	Activity	replacemant	starttime:	23400	endtime:	41400
pipe ID	2983	Activity	repair	starttime:	41400	endtime:	52200
pipe ID	5871	Activity	repair	starttime:	52200	endtime:	70200
pipe ID	1186	Activity	isolation	starttime:	70200	endtime:	73800
pipe ID	4083	Activity	repair	starttime:	73800	endtime:	84600
pipe ID	1186	Activity	replacemant	starttime:	84600	endtime:	99000
pipe ID	5775	Activity	isolation	starttime:	99000	endtime:	100800
pipe ID	4035	Activity	repair	starttime:	100800	endtime:	115200
pipe ID	5775	Activity	replacemant	starttime:	115200	endtime:	126000
pipe ID	2001	Activity	repair	starttime:	126000	endtime:	140400
pipe ID	288	Activity	replacemant	starttime:	140400	endtime:	154800
pipe ID	3414	Activity	replacemant	starttime:	154800	endtime:	180000
pipe ID	5251	Activity	replacemant	starttime:	180000	endtime:	205200
pipe ID	6023	Activity	replacemant	starttime:	205200	endtime:	219600
pipe ID	1951	Activity	replacemant	starttime:	219600	endtime:	244800
pipe ID	4988	Activity	replacemant	starttime:	244800	endtime:	270000
pipe ID	3094	Activity	replacemant	starttime:	270000	endtime:	288000
pipe ID	1807	Activity	repair	starttime:	288000	endtime:	295200
pipe ID	4882	Activity	repair	starttime:	295200	endtime:	302400
pipe ID	1657	Activity	repair	starttime:	302400	endtime:	309600
pipe ID	1464	Activity	repair	starttime:	309600	endtime:	316800
pipe ID	4622	Activity	repair	starttime:	316800	endtime:	324000
pipe ID	2430	Activity	repair	starttime:	324000	endtime:	331200
pipe ID	4584	Activity	repair	starttime:	331200	endtime:	338400
pipe ID	2440	Activity	repair	starttime:	338400	endtime:	345600
pipe ID	404	Activity	repair	starttime:	345600	endtime:	352800
pipe ID	2622	Activity	repair	starttime:	352800	endtime:	360000
pipe ID	854	Activity	repair	starttime:	360000	endtime:	367200
pipe ID	5567	Activity	repair	starttime:	367200	endtime:	374400
pipe ID	1568	Activity	repair	starttime:	374400	endtime:	381600
pipe ID	2216	Activity	repair	starttime:	381600	endtime:	392400
pipe ID	3859	Activity	repair	starttime:	392400	endtime:	399600
Crew 02							

pipe ID	163	Activity	repair	starttime:	1800	endtime:	23400
pipe ID	6005	Activity	isolation	starttime:	23400	endtime:	26100
pipe ID	6005	Activity	replacemant	starttime:	26100	endtime:	44100
pipe ID	1105	Activity	repair	starttime:	44100	endtime:	54900
pipe ID	2910	Activity	repair	starttime:	54900	endtime:	69300
pipe ID	3679	Activity	repair	starttime:	69300	endtime:	83700
pipe ID	5691	Activity	repair	starttime:	83700	endtime:	94500
pipe ID	2726	Activity	repair	starttime:	94500	endtime:	105300
pipe ID	1252	Activity	isolation	starttime:	105300	endtime:	108900
pipe ID	3875	Activity	repair	starttime:	108900	endtime:	123300
pipe ID	2307	Activity	repair	starttime:	123300	endtime:	134100
pipe ID	762	Activity	repair	starttime:	134100	endtime:	144900
pipe ID	1252	Activity	replacemant	starttime:	144900	endtime:	162900
pipe ID	2821	Activity	repair	starttime:	162900	endtime:	173700
pipe ID	3564	Activity	isolation	starttime:	173700	endtime:	176400
pipe ID	4062	Activity	repair	starttime:	176400	endtime:	187200
pipe ID	3564	Activity	replacemant	starttime:	187200	endtime:	201600
pipe ID	3104	Activity	isolation	starttime:	201600	endtime:	203400
pipe ID	2543	Activity	isolation	starttime:	203400	endtime:	205200
pipe ID	892	Activity	repair	starttime:	205200	endtime:	212400
pipe ID	2543	Activity	replacemant	starttime:	212400	endtime:	223200
pipe ID	4507	Activity	repair	starttime:	223200	endtime:	230400
pipe ID	2535	Activity	isolation	starttime:	230400	endtime:	233100
pipe ID	1865	Activity	repair	starttime:	233100	endtime:	240300
pipe ID	5778	Activity	repair	starttime:	240300	endtime:	247500
pipe ID	1724	Activity	repair	starttime:	247500	endtime:	254700
pipe ID	5042	Activity	repair	starttime:	254700	endtime:	261900
pipe ID	4915	Activity	isolation	starttime:	261900	endtime:	264600
pipe ID	4915	Activity	replacemant	starttime:	264600	endtime:	275400
pipe ID	5105	Activity	repair	starttime:	275400	endtime:	282600
pipe ID	3074	Activity	repair	starttime:	282600	endtime:	289800
pipe ID	2016	Activity	repair	starttime:	289800	endtime:	297000
pipe ID	4538	Activity	repair	starttime:	297000	endtime:	304200
pipe ID	2730	Activity	repair	starttime:	304200	endtime:	311400
pipe ID	3216	Activity	repair	starttime:	311400	endtime:	318600
pipe ID	1402	Activity	repair	starttime:	318600	endtime:	325800
pipe ID	5677	Activity	repair	starttime:	325800	endtime:	333000
pipe ID	1989	Activity	repair	starttime:	333000	endtime:	340200
pipe ID	4177	Activity	repair	starttime:	340200	endtime:	347400
pipe ID	5488	Activity	repair	starttime:	347400	endtime:	354600
pipe ID	501	Activity	repair	starttime:	354600	endtime:	361800
pipe ID	2113	Activity	repair	starttime:	361800	endtime:	372600
pipe ID	869	Activity	repair	starttime:	372600	endtime:	379800

pipe ID	3726	Activity	repair	starttime:	379800	endtime:	387000
pipe ID	3104	Activity	replacemant	starttime:	387000	endtime:	397800
pipe ID	2535	Activity	replacemant	starttime:	397800	endtime:	408600
Crew 03							
pipe ID	2408	Activity	isolation	starttime:	1800	endtime:	4500
pipe ID	4409	Activity	repair	starttime:	105300	endtime:	108900
pipe ID	2408	Activity	replacemant	starttime:	209700	endtime:	210600
pipe ID	2141	Activity	repair	starttime:	243000	endtime:	248400
pipe ID	2094	Activity	repair	starttime:	356400	endtime:	362700
pipe ID	2409	Activity	repair	starttime:	26100	endtime:	44100
pipe ID	2881	Activity	repair	starttime:	108900	endtime:	126900
pipe ID	3404	Activity	isolation	starttime:	232200	endtime:	243000
pipe ID	3404	Activity	replacemant	starttime:	248400	endtime:	259200
pipe ID	4788	Activity	repair	starttime:	362700	endtime:	373500
pipe ID	4038	Activity	repair	starttime:	4500	endtime:	26100
pipe ID	3449	Activity	repair	starttime:	44100	endtime:	58500
pipe ID	4246	Activity	repair	starttime:	58500	endtime:	72900
pipe ID	3760	Activity	repair	starttime:	72900	endtime:	83700
pipe ID	4721	Activity	repair	starttime:	83700	endtime:	105300
pipe ID	4942	Activity	repair	starttime:	126900	endtime:	141300
pipe ID	2508	Activity	isolation	starttime:	141300	endtime:	155700
pipe ID	3184	Activity	repair	starttime:	155700	endtime:	170100
pipe ID	3959	Activity	repair	starttime:	170100	endtime:	184500
pipe ID	4594	Activity	repair	starttime:	184500	endtime:	195300
pipe ID	2508	Activity	replacemant	starttime:	195300	endtime:	202500
pipe ID	3125	Activity	isolation	starttime:	202500	endtime:	209700
pipe ID	3125	Activity	replacemant	starttime:	210600	endtime:	217800
pipe ID	5959	Activity	repair	starttime:	217800	endtime:	225000
pipe ID	2114	Activity	repair	starttime:	225000	endtime:	232200
pipe ID	6041	Activity	repair	starttime:	259200	endtime:	266400
pipe ID	4764	Activity	repair	starttime:	266400	endtime:	273600
pipe ID	1373	Activity	repair	starttime:	273600	endtime:	280800
pipe ID	4022	Activity	repair	starttime:	280800	endtime:	288000
pipe ID	2053	Activity	repair	starttime:	288000	endtime:	295200
pipe ID	4880	Activity	repair	starttime:	295200	endtime:	302400
pipe ID	190	Activity	repair	starttime:	302400	endtime:	313200
pipe ID	3041	Activity	repair	starttime:	313200	endtime:	320400
pipe ID	5140	Activity	repair	starttime:	320400	endtime:	327600
pipe ID	3122	Activity	repair	starttime:	327600	endtime:	334800
pipe ID	1477	Activity	repair	starttime:	334800	endtime:	342000
pipe ID	4132	Activity	isolation	starttime:	342000	endtime:	349200
pipe ID	4132	Activity	replacemant	starttime:	349200	endtime:	356400
pipe ID	538	Activity	repair	starttime:	373500	endtime:	380700

pipe ID	3120	Activity	repair	starttime:	380700	endtime:	387900
pipe ID	4101	Activity	repair	starttime:	387900	endtime:	395100
pipe ID	2816	Activity	repair	starttime:	395100	endtime:	402300

Table C3. The detail restoration schedule of the 3 crews for scenario 3

Crew 01							
Pipe ID	3948	Activity	isolation	starttime:	1800	endtime:	5400
Pipe ID	282	Activity	isolation	starttime:	5400	endtime:	7200
Pipe ID	5198	Activity	repair	starttime:	7200	endtime:	18000
Pipe ID	1004	Activity	repair	starttime:	18000	endtime:	32400
Pipe ID	282	Activity	replacemant	starttime:	32400	endtime:	46800
Pipe ID	682	Activity	repair	starttime:	46800	endtime:	57600
Pipe ID	2695	Activity	repair	starttime:	57600	endtime:	68400
Pipe ID	3979	Activity	isolation	starttime:	68400	endtime:	69300
Pipe ID	3264	Activity	repair	starttime:	69300	endtime:	83700
Pipe ID	1384	Activity	repair	starttime:	83700	endtime:	98100
Pipe ID	2710	Activity	repair	starttime:	98100	endtime:	108900
Pipe ID	2252	Activity	repair	starttime:	108900	endtime:	126900
Pipe ID	2913	Activity	repair	starttime:	126900	endtime:	141300
Pipe ID	3414	Activity	repair	starttime:	141300	endtime:	155700
Pipe ID	3658	Activity	repair	starttime:	155700	endtime:	173700
Pipe ID	2604	Activity	repair	starttime:	173700	endtime:	188100
Pipe ID	338	Activity	repair	starttime:	188100	endtime:	202500
Pipe ID	5865	Activity	repair	starttime:	202500	endtime:	216900
Pipe ID	3399	Activity	repair	starttime:	216900	endtime:	234900
Pipe ID	3903	Activity	repair	starttime:	234900	endtime:	252900
Pipe ID	3979	Activity	replacemant	starttime:	252900	endtime:	270900
Pipe ID	3948	Activity	replacemant	starttime:	270900	endtime:	296100
Pipe ID	4535	Activity	repair	starttime:	296100	endtime:	303300
Pipe ID	3122	Activity	isolation	starttime:	303300	endtime:	306900
Pipe ID	3122	Activity	replacemant	starttime:	306900	endtime:	317700
Pipe ID	1657	Activity	isolation	starttime:	317700	endtime:	321300
Pipe ID	1619	Activity	repair	starttime:	321300	endtime:	328500
Pipe ID	1657	Activity	replacemant	starttime:	328500	endtime:	339300
Pipe ID	5878	Activity	repair	starttime:	339300	endtime:	346500
Pipe ID	267	Activity	repair	starttime:	346500	endtime:	353700
Pipe ID	4125	Activity	isolation	starttime:	353700	endtime:	354600
Pipe ID	1314	Activity	repair	starttime:	354600	endtime:	361800
Pipe ID	3149	Activity	repair	starttime:	361800	endtime:	369000
Pipe ID	52	Activity	repair	starttime:	369000	endtime:	376200
Pipe ID	5128	Activity	repair	starttime:	376200	endtime:	383400
Pipe ID	5013	Activity	repair	starttime:	383400	endtime:	390600
Pipe ID	4125	Activity	replacemant	starttime:	390600	endtime:	401400
Pipe ID	5252	Activity	repair	starttime:	401400	endtime:	408600
Pipe ID	1928	Activity	repair	starttime:	408600	endtime:	415800
Pipe ID	4807	Activity	repair	starttime:	415800	endtime:	423000
Pipe ID	4265	Activity	repair	starttime:	423000	endtime:	430200

Pipe ID	2468	Activity	repair	starttime:	430200	endtime:	437400
Pipe ID	4341	Activity	repair	starttime:	437400	endtime:	444600
Pipe ID	1945	Activity	repair	starttime:	444600	endtime:	451800
Pipe ID	5420	Activity	repair	starttime:	451800	endtime:	459000
Pipe ID	1699	Activity	repair	starttime:	459000	endtime:	466200
Pipe ID	1007	Activity	repair	starttime:	466200	endtime:	473400
Pipe ID	381	Activity	repair	starttime:	473400	endtime:	484200
Pipe ID	1874	Activity	repair	starttime:	484200	endtime:	491400
Pipe ID	1201	Activity	repair	starttime:	491400	endtime:	498600
Crew 02							
Pipe ID	5783	Activity	repair	starttime:	1800	endtime:	12600
Pipe ID	716	Activity	isolation	starttime:	12600	endtime:	14400
Pipe ID	1972	Activity	isolation	starttime:	14400	endtime:	17100
Pipe ID	3435	Activity	isolation	starttime:	17100	endtime:	18900
Pipe ID	1972	Activity	replacemant	starttime:	18900	endtime:	33300
Pipe ID	92	Activity	isolation	starttime:	33300	endtime:	36900
Pipe ID	140	Activity	repair	starttime:	36900	endtime:	54900
Pipe ID	168	Activity	repair	starttime:	54900	endtime:	83700
Pipe ID	3402	Activity	repair	starttime:	83700	endtime:	98100
Pipe ID	4899	Activity	repair	starttime:	98100	endtime:	116100
Pipe ID	3804	Activity	repair	starttime:	116100	endtime:	130500
Pipe ID	1922	Activity	repair	starttime:	130500	endtime:	144900
Pipe ID	716	Activity	replacemant	starttime:	144900	endtime:	173700
Pipe ID	5983	Activity	repair	starttime:	173700	endtime:	184500
Pipe ID	3082	Activity	repair	starttime:	184500	endtime:	195300
Pipe ID	2825	Activity	repair	starttime:	195300	endtime:	209700
Pipe ID	2263	Activity	repair	starttime:	209700	endtime:	224100
Pipe ID	92	Activity	replacemant	starttime:	224100	endtime:	249300
Pipe ID	3435	Activity	replacemant	starttime:	249300	endtime:	267300
Pipe ID	2140	Activity	isolation	starttime:	267300	endtime:	268200
Pipe ID	2525	Activity	repair	starttime:	268200	endtime:	275400
Pipe ID	198	Activity	repair	starttime:	275400	endtime:	282600
Pipe ID	2999	Activity	isolation	starttime:	282600	endtime:	284400
Pipe ID	5604	Activity	isolation	starttime:	284400	endtime:	285300
Pipe ID	3714	Activity	isolation	starttime:	285300	endtime:	288900
Pipe ID	3714	Activity	replacemant	starttime:	288900	endtime:	299700
Pipe ID	2152	Activity	repair	starttime:	299700	endtime:	306900
Pipe ID	4379	Activity	repair	starttime:	306900	endtime:	314100
Pipe ID	2416	Activity	repair	starttime:	314100	endtime:	321300
Pipe ID	4594	Activity	repair	starttime:	321300	endtime:	328500
Pipe ID	2999	Activity	replacemant	starttime:	328500	endtime:	339300
Pipe ID	5604	Activity	replacemant	starttime:	339300	endtime:	350100
Pipe ID	114	Activity	repair	starttime:	350100	endtime:	357300

Pipe ID	3558	Activity	repair	starttime:	357300	endtime:	364500
Pipe ID	657	Activity	repair	starttime:	364500	endtime:	371700
Pipe ID	5946	Activity	isolation	starttime:	371700	endtime:	373500
Pipe ID	2318	Activity	isolation	starttime:	373500	endtime:	376200
Pipe ID	5946	Activity	replacemant	starttime:	376200	endtime:	387000
Pipe ID	2318	Activity	replacemant	starttime:	387000	endtime:	397800
Pipe ID	3348	Activity	repair	starttime:	397800	endtime:	405000
Pipe ID	2939	Activity	repair	starttime:	405000	endtime:	412200
Pipe ID	3071	Activity	repair	starttime:	412200	endtime:	419400
Pipe ID	2747	Activity	repair	starttime:	419400	endtime:	426600
Pipe ID	1989	Activity	repair	starttime:	426600	endtime:	433800
Pipe ID	4889	Activity	repair	starttime:	433800	endtime:	441000
Pipe ID	4101	Activity	repair	starttime:	441000	endtime:	448200
Pipe ID	4642	Activity	repair	starttime:	448200	endtime:	455400
Pipe ID	2162	Activity	repair	starttime:	455400	endtime:	462600
Pipe ID	2140	Activity	replacemant	starttime:	462600	endtime:	473400
Pipe ID	424	Activity	repair	starttime:	473400	endtime:	484200
Pipe ID	1299	Activity	repair	starttime:	484200	endtime:	491400
Crew 03							
Pipe ID	2315	Activity	repair	starttime:	1800	endtime:	12600
Pipe ID	5125	Activity	repair	starttime:	12600	endtime:	27000
Pipe ID	3403	Activity	repair	starttime:	27000	endtime:	41400
Pipe ID	1788	Activity	repair	starttime:	41400	endtime:	55800
Pipe ID	2554	Activity	repair	starttime:	55800	endtime:	66600
Pipe ID	2792	Activity	repair	starttime:	66600	endtime:	77400
Pipe ID	3836	Activity	repair	starttime:	77400	endtime:	91800
Pipe ID	2904	Activity	repair	starttime:	91800	endtime:	106200
Pipe ID	1902	Activity	repair	starttime:	106200	endtime:	120600
Pipe ID	5456	Activity	repair	starttime:	120600	endtime:	138600
Pipe ID	3380	Activity	repair	starttime:	138600	endtime:	153000
Pipe ID	798	Activity	repair	starttime:	153000	endtime:	163800
Pipe ID	341	Activity	repair	starttime:	163800	endtime:	178200
Pipe ID	3032	Activity	repair	starttime:	178200	endtime:	192600
Pipe ID	994	Activity	repair	starttime:	192600	endtime:	203400
Pipe ID	3019	Activity	repair	starttime:	203400	endtime:	217800
Pipe ID	770	Activity	repair	starttime:	217800	endtime:	243000
Pipe ID	771	Activity	repair	starttime:	243000	endtime:	253800
Pipe ID	5144	Activity	isolation	starttime:	253800	endtime:	255600
Pipe ID	5088	Activity	repair	starttime:	255600	endtime:	262800
Pipe ID	5144	Activity	replacemant	starttime:	262800	endtime:	273600
Pipe ID	1019	Activity	isolation	starttime:	273600	endtime:	275400
Pipe ID	1019	Activity	replacemant	starttime:	275400	endtime:	286200
Pipe ID	1737	Activity	repair	starttime:	286200	endtime:	293400

Pipe ID	4174	Activity	isolation	starttime:	293400	endtime:	296100
Pipe ID	5579	Activity	repair	starttime:	296100	endtime:	303300
Pipe ID	3469	Activity	repair	starttime:	303300	endtime:	310500
Pipe ID	1916	Activity	repair	starttime:	310500	endtime:	317700
Pipe ID	4704	Activity	repair	starttime:	317700	endtime:	324900
Pipe ID	4174	Activity	replacemant	starttime:	324900	endtime:	335700
Pipe ID	695	Activity	repair	starttime:	335700	endtime:	342900
Pipe ID	2116	Activity	isolation	starttime:	342900	endtime:	343800
Pipe ID	5423	Activity	repair	starttime:	343800	endtime:	351000
Pipe ID	1610	Activity	repair	starttime:	351000	endtime:	358200
Pipe ID	906	Activity	repair	starttime:	358200	endtime:	365400
Pipe ID	3859	Activity	repair	starttime:	365400	endtime:	372600
Pipe ID	2116	Activity	replacemant	starttime:	372600	endtime:	383400
Pipe ID	3088	Activity	repair	starttime:	383400	endtime:	390600
Pipe ID	1588	Activity	isolation	starttime:	390600	endtime:	392400
Pipe ID	1588	Activity	replacemant	starttime:	392400	endtime:	403200
Pipe ID	1796	Activity	repair	starttime:	403200	endtime:	410400
Pipe ID	3587	Activity	repair	starttime:	410400	endtime:	417600
Pipe ID	3079	Activity	repair	starttime:	417600	endtime:	424800
Pipe ID	4503	Activity	repair	starttime:	424800	endtime:	432000
Pipe ID	1179	Activity	repair	starttime:	432000	endtime:	439200
Pipe ID	2291	Activity	repair	starttime:	439200	endtime:	446400
Pipe ID	4972	Activity	repair	starttime:	446400	endtime:	453600
Pipe ID	1016	Activity	repair	starttime:	453600	endtime:	460800
Pipe ID	2212	Activity	repair	starttime:	460800	endtime:	471600
Pipe ID	3257	Activity	repair	starttime:	471600	endtime:	478800
Pipe ID	2663	Activity	repair	starttime:	478800	endtime:	486000
Pipe ID	2901	Activity	repair	starttime:	486000	endtime:	493200

Table C4. The detail restoration schedule of the 3 crews for scenario 4

Crew 01							
Pipe ID	163	Activity	isolation	starttime	1800	endtime	3600
Pipe ID	163	Activity	replacemant	starttime	3600	endtime	39600
Pipe ID	4139	Activity	repair	starttime	39600	endtime	57600
Pipe ID	2992	Activity	repair	starttime	57600	endtime	68400
Pipe ID	3045	Activity	repair	starttime	68400	endtime	82800
Pipe ID	3758	Activity	isolation	starttime	82800	endtime	86400
Pipe ID	245	Activity	isolation	starttime	86400	endtime	89100
Pipe ID	3758	Activity	replacemant	starttime	89100	endtime	103500
Pipe ID	2721	Activity	isolation	starttime	103500	endtime	105300
Pipe ID	2	Activity	repair	starttime	105300	endtime	123300
Pipe ID	2721	Activity	replacemant	starttime	123300	endtime	137700
Pipe ID	3693	Activity	isolation	starttime	137700	endtime	144000
Pipe ID	5362	Activity	repair	starttime	144000	endtime	158400
Pipe ID	3488	Activity	repair	starttime	158400	endtime	172800
Pipe ID	3531	Activity	repair	starttime	172800	endtime	180000
Pipe ID	610	Activity	isolation	starttime	180000	endtime	185400
Pipe ID	610	Activity	replacemant	starttime	185400	endtime	199800
Pipe ID	5120	Activity	isolation	starttime	199800	endtime	201600
Pipe ID	2584	Activity	repair	starttime	201600	endtime	208800
Pipe ID	5932	Activity	repair	starttime	208800	endtime	216000
Pipe ID	5277	Activity	isolation	starttime	216000	endtime	217800
Pipe ID	5277	Activity	replacemant	starttime	217800	endtime	228600
Pipe ID	5120	Activity	replacemant	starttime	228600	endtime	239400
Pipe ID	5089	Activity	repair	starttime	239400	endtime	246600
Pipe ID	2851	Activity	repair	starttime	246600	endtime	253800
Pipe ID	2145	Activity	repair	starttime	253800	endtime	268200
Pipe ID	842	Activity	isolation	starttime	268200	endtime	270000
Pipe ID	4889	Activity	repair	starttime	270000	endtime	277200
Pipe ID	349	Activity	repair	starttime	277200	endtime	284400
Pipe ID	4882	Activity	repair	starttime	284400	endtime	291600
Pipe ID	3693	Activity	replacemant	starttime	291600	endtime	309600
Pipe ID	4652	Activity	repair	starttime	309600	endtime	316800
Pipe ID	1819	Activity	repair	starttime	316800	endtime	324000
Pipe ID	5198	Activity	repair	starttime	324000	endtime	334800
Pipe ID	3553	Activity	repair	starttime	334800	endtime	342000
Pipe ID	2897	Activity	repair	starttime	342000	endtime	356400
Pipe ID	1425	Activity	repair	starttime	356400	endtime	370800
Pipe ID	2689	Activity	repair	starttime	370800	endtime	378000
Pipe ID	1966	Activity	repair	starttime	378000	endtime	392400
Pipe ID	4594	Activity	repair	starttime	392400	endtime	399600
Pipe ID	197	Activity	repair	starttime	399600	endtime	406800

Pipe ID	3466	Activity	repair	starttime	406800	endtime	414000
Pipe ID	245	Activity	replacemant	starttime	414000	endtime	432000
Pipe ID	3147	Activity	repair	starttime	432000	endtime	439200
Pipe ID	2307	Activity	repair	starttime	439200	endtime	450000
Pipe ID	4807	Activity	repair	starttime	450000	endtime	457200
Pipe ID	842	Activity	replacemant	starttime	457200	endtime	468000
Pipe ID	4624	Activity	isolation	starttime	468000	endtime	470700
Pipe ID	4624	Activity	replacemant	starttime	470700	endtime	481500
Crew 02							
Pipe ID	4805	Activity	repair	starttime	1800	endtime	23400
Pipe ID	1844	Activity	isolation	starttime	23400	endtime	25200
Pipe ID	5942	Activity	isolation	starttime	25200	endtime	27000
Pipe ID	1558	Activity	isolation	starttime	27000	endtime	30600
Pipe ID	5995	Activity	repair	starttime	30600	endtime	48600
Pipe ID	1162	Activity	isolation	starttime	48600	endtime	51300
Pipe ID	1414	Activity	repair	starttime	51300	endtime	62100
Pipe ID	1162	Activity	replacemant	starttime	62100	endtime	72900
Pipe ID	5988	Activity	repair	starttime	72900	endtime	87300
Pipe ID	3123	Activity	repair	starttime	87300	endtime	101700
Pipe ID	1844	Activity	replacemant	starttime	101700	endtime	119700
Pipe ID	6016	Activity	repair	starttime	119700	endtime	134100
Pipe ID	3571	Activity	repair	starttime	134100	endtime	148500
Pipe ID	5942	Activity	replacemant	starttime	148500	endtime	173700
Pipe ID	5118	Activity	repair	starttime	173700	endtime	180900
Pipe ID	5344	Activity	repair	starttime	180900	endtime	198900
Pipe ID	2914	Activity	isolation	starttime	198900	endtime	200700
Pipe ID	1863	Activity	repair	starttime	200700	endtime	207900
Pipe ID	1280	Activity	isolation	starttime	207900	endtime	209700
Pipe ID	5873	Activity	repair	starttime	209700	endtime	216900
Pipe ID	4010	Activity	isolation	starttime	216900	endtime	218700
Pipe ID	4010	Activity	replacemant	starttime	218700	endtime	229500
Pipe ID	1820	Activity	repair	starttime	229500	endtime	236700
Pipe ID	5287	Activity	isolation	starttime	236700	endtime	241200
Pipe ID	5287	Activity	replacemant	starttime	241200	endtime	252000
Pipe ID	2098	Activity	repair	starttime	252000	endtime	262800
Pipe ID	1618	Activity	isolation	starttime	262800	endtime	263700
Pipe ID	2455	Activity	repair	starttime	263700	endtime	270900
Pipe ID	255	Activity	repair	starttime	270900	endtime	278100
Pipe ID	3679	Activity	repair	starttime	278100	endtime	292500
Pipe ID	5899	Activity	repair	starttime	292500	endtime	299700
Pipe ID	5164	Activity	repair	starttime	299700	endtime	306900
Pipe ID	3456	Activity	repair	starttime	306900	endtime	314100
Pipe ID	5183	Activity	repair	starttime	314100	endtime	321300

Pipe ID	1280	Activity	replacemant	starttime	321300	endtime	332100
Pipe ID	2954	Activity	repair	starttime	332100	endtime	339300
Pipe ID	3908	Activity	repair	starttime	339300	endtime	346500
Pipe ID	3314	Activity	repair	starttime	346500	endtime	353700
Pipe ID	5718	Activity	repair	starttime	353700	endtime	360900
Pipe ID	3558	Activity	repair	starttime	360900	endtime	368100
Pipe ID	5859	Activity	repair	starttime	368100	endtime	375300
Pipe ID	4552	Activity	repair	starttime	375300	endtime	386100
Pipe ID	580	Activity	repair	starttime	386100	endtime	393300
Pipe ID	1618	Activity	replacemant	starttime	393300	endtime	404100
Pipe ID	2914	Activity	replacemant	starttime	404100	endtime	414900
Pipe ID	1558	Activity	replacemant	starttime	414900	endtime	432900
Pipe ID	1167	Activity	repair	starttime	432900	endtime	440100
Pipe ID	2759	Activity	repair	starttime	440100	endtime	447300
Pipe ID	3634	Activity	repair	starttime	447300	endtime	461700
Pipe ID	2501	Activity	repair	starttime	461700	endtime	468900
Crew 03							
Pipe ID	1813	Activity	isolation	starttime	1800	endtime	3600
Pipe ID	2269	Activity	isolation	starttime	3600	endtime	7200
Pipe ID	816	Activity	repair	starttime	7200	endtime	21600
Pipe ID	2069	Activity	isolation	starttime	21600	endtime	23400
Pipe ID	1869	Activity	repair	starttime	23400	endtime	37800
Pipe ID	1612	Activity	repair	starttime	37800	endtime	52200
Pipe ID	2069	Activity	replacemant	starttime	52200	endtime	88200
Pipe ID	1813	Activity	replacemant	starttime	88200	endtime	106200
Pipe ID	3557	Activity	isolation	starttime	106200	endtime	110700
Pipe ID	2137	Activity	repair	starttime	110700	endtime	121500
Pipe ID	2269	Activity	replacemant	starttime	121500	endtime	135900
Pipe ID	5357	Activity	repair	starttime	135900	endtime	146700
Pipe ID	791	Activity	repair	starttime	146700	endtime	164700
Pipe ID	2844	Activity	repair	starttime	164700	endtime	182700
Pipe ID	5123	Activity	repair	starttime	182700	endtime	189900
Pipe ID	2060	Activity	isolation	starttime	189900	endtime	190800
Pipe ID	3624	Activity	repair	starttime	190800	endtime	205200
Pipe ID	5793	Activity	repair	starttime	205200	endtime	212400
Pipe ID	3433	Activity	repair	starttime	212400	endtime	223200
Pipe ID	5901	Activity	repair	starttime	223200	endtime	230400
Pipe ID	2062	Activity	isolation	starttime	230400	endtime	232200
Pipe ID	5550	Activity	repair	starttime	232200	endtime	239400
Pipe ID	2060	Activity	replacemant	starttime	239400	endtime	250200
Pipe ID	5649	Activity	repair	starttime	250200	endtime	257400
Pipe ID	1649	Activity	repair	starttime	257400	endtime	264600
Pipe ID	1031	Activity	repair	starttime	264600	endtime	271800

Pipe ID	1098	Activity	repair	starttime	271800	endtime	279000
Pipe ID	1538	Activity	repair	starttime	279000	endtime	286200
Pipe ID	150	Activity	isolation	starttime	286200	endtime	287100
Pipe ID	788	Activity	repair	starttime	287100	endtime	301500
Pipe ID	175	Activity	repair	starttime	301500	endtime	308700
Pipe ID	2282	Activity	repair	starttime	308700	endtime	319500
Pipe ID	150	Activity	replacemant	starttime	319500	endtime	330300
Pipe ID	1996	Activity	repair	starttime	330300	endtime	337500
Pipe ID	695	Activity	repair	starttime	337500	endtime	344700
Pipe ID	2977	Activity	repair	starttime	344700	endtime	351900
Pipe ID	5408	Activity	repair	starttime	351900	endtime	359100
Pipe ID	4499	Activity	repair	starttime	359100	endtime	366300
Pipe ID	699	Activity	repair	starttime	366300	endtime	380700
Pipe ID	1107	Activity	repair	starttime	380700	endtime	387900
Pipe ID	3557	Activity	replacemant	starttime	387900	endtime	413100
Pipe ID	1614	Activity	repair	starttime	413100	endtime	420300
Pipe ID	2791	Activity	repair	starttime	420300	endtime	427500
Pipe ID	4757	Activity	repair	starttime	427500	endtime	434700
Pipe ID	1341	Activity	repair	starttime	434700	endtime	445500
Pipe ID	1377	Activity	repair	starttime	445500	endtime	452700
Pipe ID	4454	Activity	repair	starttime	452700	endtime	459900
Pipe ID	2062	Activity	replacemant	starttime	459900	endtime	470700

Table C5. The detail restoration schedule of the 3 crews for scenario 5

Crew 01							
Pipe ID	2115	Activity	isolation	starttime	1800	endtime	3600
Pipe ID	91	Activity	isolation	starttime	3600	endtime	5400
Pipe ID	91	Activity	replacemant	starttime	5400	endtime	23400
Pipe ID	2115	Activity	replacemant	starttime	23400	endtime	37800
Pipe ID	3019	Activity	isolation	starttime	37800	endtime	43200
Pipe ID	3842	Activity	repair	starttime	43200	endtime	54000
Pipe ID	1832	Activity	repair	starttime	54000	endtime	68400
Pipe ID	1540	Activity	isolation	starttime	68400	endtime	69300
Pipe ID	1540	Activity	replacemant	starttime	69300	endtime	83700
Pipe ID	4805	Activity	repair	starttime	83700	endtime	105300
Pipe ID	1794	Activity	repair	starttime	105300	endtime	119700
Pipe ID	3536	Activity	repair	starttime	119700	endtime	130500
Pipe ID	3019	Activity	replacemant	starttime	130500	endtime	148500
Pipe ID	3409	Activity	repair	starttime	148500	endtime	162900
Pipe ID	2626	Activity	repair	starttime	162900	endtime	177300
Pipe ID	1060	Activity	repair	starttime	177300	endtime	191700
Pipe ID	1640	Activity	repair	starttime	191700	endtime	206100
Pipe ID	3123	Activity	repair	starttime	206100	endtime	220500
Pipe ID	335	Activity	repair	starttime	220500	endtime	234900
Pipe ID	4316	Activity	repair	starttime	234900	endtime	245700
Pipe ID	2162	Activity	isolation	starttime	245700	endtime	247500
Pipe ID	1857	Activity	repair	starttime	247500	endtime	254700
Pipe ID	587	Activity	repair	starttime	254700	endtime	261900
Pipe ID	90	Activity	repair	starttime	261900	endtime	269100
Pipe ID	2600	Activity	repair	starttime	269100	endtime	276300
Pipe ID	1007	Activity	repair	starttime	276300	endtime	283500
Pipe ID	1352	Activity	repair	starttime	283500	endtime	290700
Pipe ID	1631	Activity	isolation	starttime	290700	endtime	292500
Pipe ID	3136	Activity	isolation	starttime	292500	endtime	297900
Pipe ID	2162	Activity	replacemant	starttime	297900	endtime	308700
Pipe ID	5280	Activity	repair	starttime	308700	endtime	315900
Pipe ID	5004	Activity	isolation	starttime	315900	endtime	317700
Pipe ID	5004	Activity	replacemant	starttime	317700	endtime	328500
Pipe ID	3216	Activity	repair	starttime	328500	endtime	335700
Pipe ID	4386	Activity	repair	starttime	335700	endtime	342900
Pipe ID	772	Activity	repair	starttime	342900	endtime	350100
Pipe ID	246	Activity	isolation	starttime	350100	endtime	351000
Pipe ID	390	Activity	repair	starttime	351000	endtime	358200

Pipe ID	5458	Activity	isolation	starttime	358200	endtime	365400
Pipe ID	246	Activity	replacemant	starttime	365400	endtime	376200
Pipe ID	60	Activity	isolation	starttime	376200	endtime	378900
Pipe ID	5207	Activity	repair	starttime	378900	endtime	386100
Pipe ID	60	Activity	replacemant	starttime	386100	endtime	396900
Pipe ID	2772	Activity	repair	starttime	396900	endtime	404100
Pipe ID	5458	Activity	replacemant	starttime	404100	endtime	414900
Pipe ID	1989	Activity	repair	starttime	414900	endtime	422100
Pipe ID	3136	Activity	replacemant	starttime	422100	endtime	432900
Pipe ID	1631	Activity	replacemant	starttime	432900	endtime	443700
Crew 02							
Pipe ID	5865	Activity	repair	starttime	1800	endtime	16200
Pipe ID	3825	Activity	isolation	starttime	16200	endtime	19800
Pipe ID	1926	Activity	repair	starttime	19800	endtime	34200
Pipe ID	6012	Activity	repair	starttime	34200	endtime	48600
Pipe ID	4129	Activity	isolation	starttime	48600	endtime	50400
Pipe ID	3723	Activity	repair	starttime	50400	endtime	64800
Pipe ID	2050	Activity	isolation	starttime	64800	endtime	69300
Pipe ID	2050	Activity	replacemant	starttime	69300	endtime	83700
Pipe ID	3690	Activity	repair	starttime	83700	endtime	98100
Pipe ID	1558	Activity	repair	starttime	98100	endtime	112500
Pipe ID	3615	Activity	repair	starttime	112500	endtime	123300
Pipe ID	5022	Activity	repair	starttime	123300	endtime	141300
Pipe ID	721	Activity	isolation	starttime	141300	endtime	144900
Pipe ID	721	Activity	replacemant	starttime	144900	endtime	155700
Pipe ID	6005	Activity	repair	starttime	155700	endtime	170100
Pipe ID	626	Activity	repair	starttime	170100	endtime	184500
Pipe ID	3825	Activity	replacemant	starttime	184500	endtime	209700
Pipe ID	4129	Activity	replacemant	starttime	209700	endtime	224100
Pipe ID	3121	Activity	repair	starttime	224100	endtime	234900
Pipe ID	3547	Activity	repair	starttime	234900	endtime	249300
Pipe ID	5893	Activity	repair	starttime	249300	endtime	256500
Pipe ID	2972	Activity	repair	starttime	256500	endtime	263700
Pipe ID	4748	Activity	isolation	starttime	263700	endtime	265500
Pipe ID	1028	Activity	isolation	starttime	265500	endtime	268200
Pipe ID	5105	Activity	isolation	starttime	268200	endtime	269100
Pipe ID	5100	Activity	repair	starttime	269100	endtime	276300
Pipe ID	5105	Activity	replacemant	starttime	276300	endtime	287100
Pipe ID	2404	Activity	isolation	starttime	287100	endtime	289800
Pipe ID	475	Activity	isolation	starttime	289800	endtime	290700
Pipe ID	2404	Activity	replacemant	starttime	290700	endtime	301500

Pipe ID	3720	Activity	repair	starttime	301500	endtime	308700
Pipe ID	1947	Activity	repair	starttime	308700	endtime	315900
Pipe ID	1402	Activity	isolation	starttime	315900	endtime	316800
Pipe ID	3049	Activity	repair	starttime	316800	endtime	324000
Pipe ID	1402	Activity	replacemant	starttime	324000	endtime	334800
Pipe ID	4652	Activity	isolation	starttime	334800	endtime	335700
Pipe ID	2212	Activity	repair	starttime	335700	endtime	346500
Pipe ID	2651	Activity	repair	starttime	346500	endtime	353700
Pipe ID	4652	Activity	replacemant	starttime	353700	endtime	364500
Pipe ID	475	Activity	replacemant	starttime	364500	endtime	375300
Pipe ID	3807	Activity	isolation	starttime	375300	endtime	378000
Pipe ID	3807	Activity	replacemant	starttime	378000	endtime	388800
Pipe ID	1028	Activity	replacemant	starttime	388800	endtime	399600
Pipe ID	154	Activity	repair	starttime	399600	endtime	406800
Pipe ID	3762	Activity	repair	starttime	406800	endtime	414000
Pipe ID	4889	Activity	repair	starttime	414000	endtime	421200
Pipe ID	4748	Activity	replacemant	starttime	421200	endtime	432000
Pipe ID	4671	Activity	repair	starttime	432000	endtime	439200
Pipe ID	5523	Activity	repair	starttime	439200	endtime	446400
Crew 03							
Pipe ID	4117	Activity	isolation	starttime	1800	endtime	3600
Pipe ID	3922	Activity	isolation	starttime	3600	endtime	5400
Pipe ID	378	Activity	isolation	starttime	5400	endtime	7200
Pipe ID	838	Activity	repair	starttime	7200	endtime	18000
Pipe ID	5194	Activity	repair	starttime	18000	endtime	32400
Pipe ID	1902	Activity	isolation	starttime	32400	endtime	34200
Pipe ID	1902	Activity	replacemant	starttime	34200	endtime	52200
Pipe ID	5688	Activity	repair	starttime	52200	endtime	66600
Pipe ID	2068	Activity	repair	starttime	66600	endtime	88200
Pipe ID	3754	Activity	repair	starttime	88200	endtime	106200
Pipe ID	2464	Activity	repair	starttime	106200	endtime	124200
Pipe ID	378	Activity	replacemant	starttime	124200	endtime	138600
Pipe ID	3398	Activity	isolation	starttime	138600	endtime	142200
Pipe ID	3398	Activity	replacemant	starttime	142200	endtime	167400
Pipe ID	3613	Activity	repair	starttime	167400	endtime	178200
Pipe ID	1936	Activity	repair	starttime	178200	endtime	192600
Pipe ID	4093	Activity	repair	starttime	192600	endtime	203400
Pipe ID	4065	Activity	repair	starttime	203400	endtime	214200
Pipe ID	809	Activity	repair	starttime	214200	endtime	228600
Pipe ID	3800	Activity	repair	starttime	228600	endtime	239400
Pipe ID	3922	Activity	replacemant	starttime	239400	endtime	264600

Pipe ID	4117	Activity	replacemant	starttime	264600	endtime	289800
Pipe ID	4379	Activity	repair	starttime	289800	endtime	297000
Pipe ID	2596	Activity	repair	starttime	297000	endtime	304200
Pipe ID	98	Activity	repair	starttime	304200	endtime	311400
Pipe ID	5432	Activity	repair	starttime	311400	endtime	318600
Pipe ID	1731	Activity	repair	starttime	318600	endtime	325800
Pipe ID	1282	Activity	isolation	starttime	325800	endtime	326700
Pipe ID	2804	Activity	isolation	starttime	326700	endtime	333000
Pipe ID	1282	Activity	replacemant	starttime	333000	endtime	343800
Pipe ID	2804	Activity	replacemant	starttime	343800	endtime	354600
Pipe ID	253	Activity	repair	starttime	354600	endtime	361800
Pipe ID	4022	Activity	repair	starttime	361800	endtime	369000
Pipe ID	1032	Activity	repair	starttime	369000	endtime	376200
Pipe ID	5845	Activity	repair	starttime	376200	endtime	383400
Pipe ID	2646	Activity	repair	starttime	383400	endtime	390600
Pipe ID	4594	Activity	isolation	starttime	390600	endtime	392400
Pipe ID	5550	Activity	repair	starttime	392400	endtime	399600
Pipe ID	4594	Activity	replacemant	starttime	399600	endtime	410400
Pipe ID	1418	Activity	repair	starttime	410400	endtime	417600
Pipe ID	88	Activity	repair	starttime	417600	endtime	432000
Pipe ID	153	Activity	repair	starttime	432000	endtime	439200

Annex D

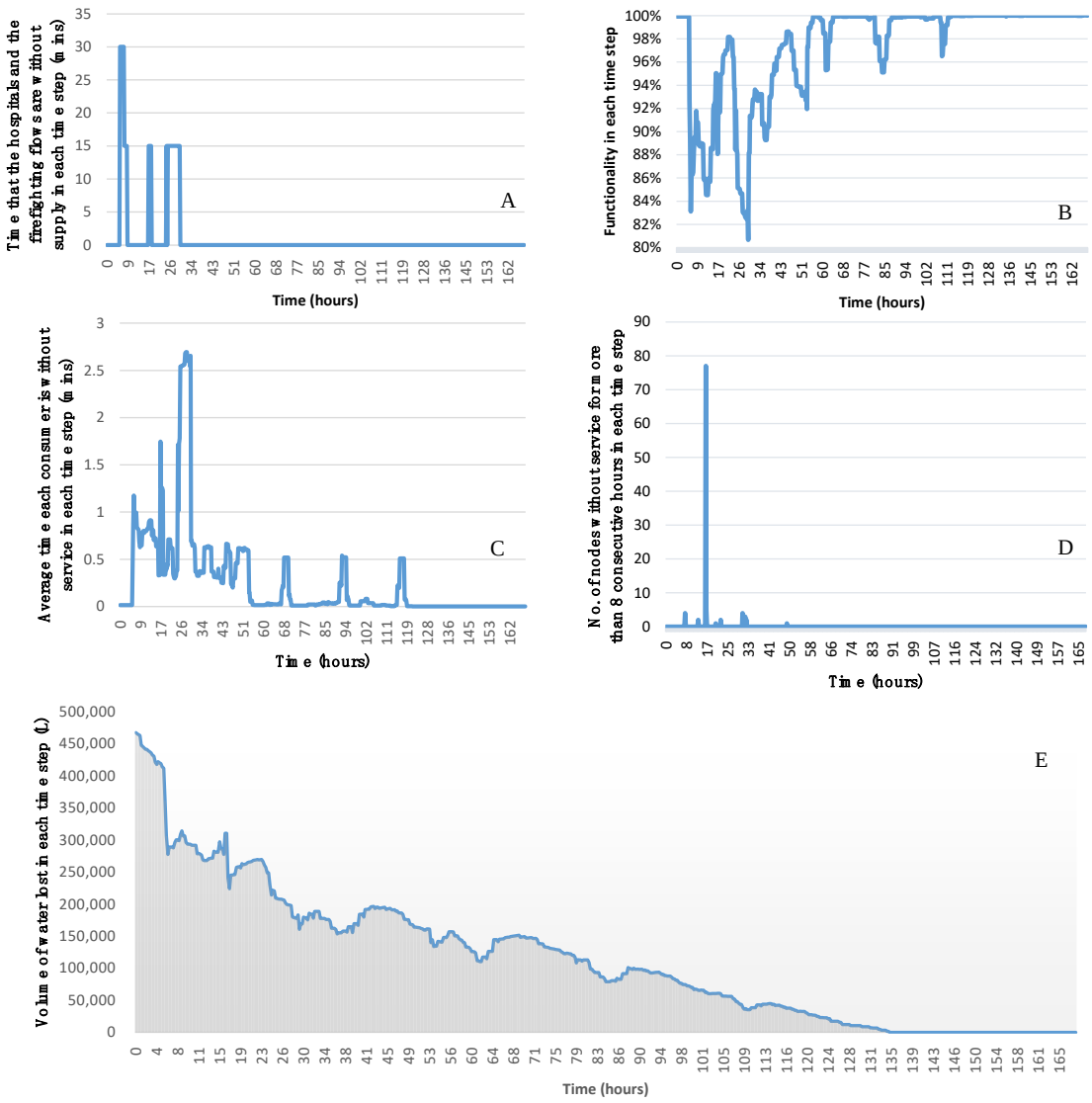

Figure D1. The change of evaluation index with time step for scenario 1. A) Time that the hospitals and the firefighting flows are without supply in each time step (mins); B) Functionality in each time step (%); C) Average time each consumer is without service in each time step (mins); D) No. of nodes without service for more than 8 consecutive hours in each time step; and E) Volume of water lost in each time step (L)

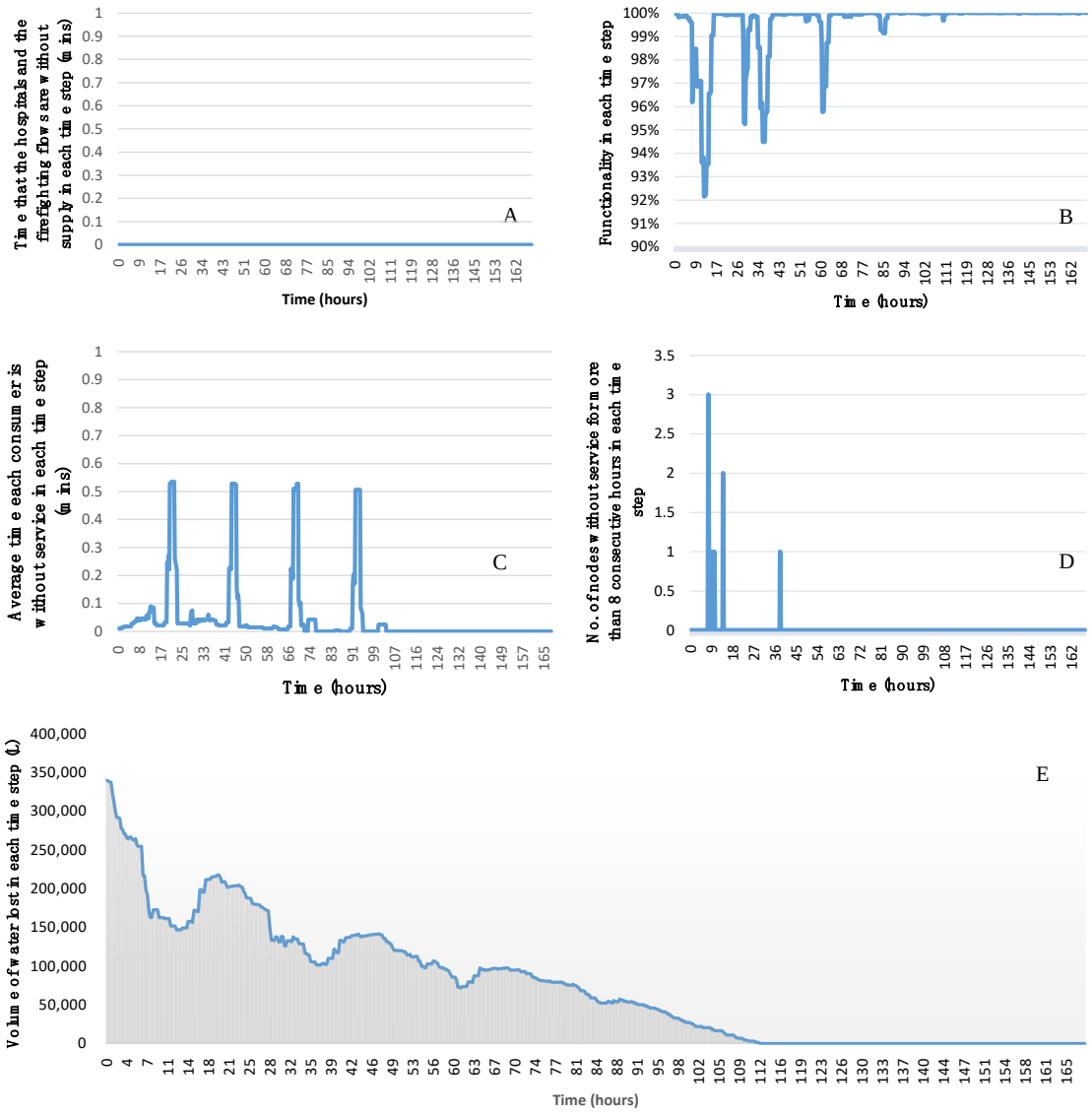

Figure D2. The change of evaluation index with time step for scenario 2. A) Time that the hospitals and the firefighting flows are without supply in each time step (mins); B) Functionality in each time step (%); C) Average time each consumer is without service in each time step (mins); D) No. of nodes without service for more than 8 consecutive hours in each time step; and E) Volume of water lost in each time step (L)

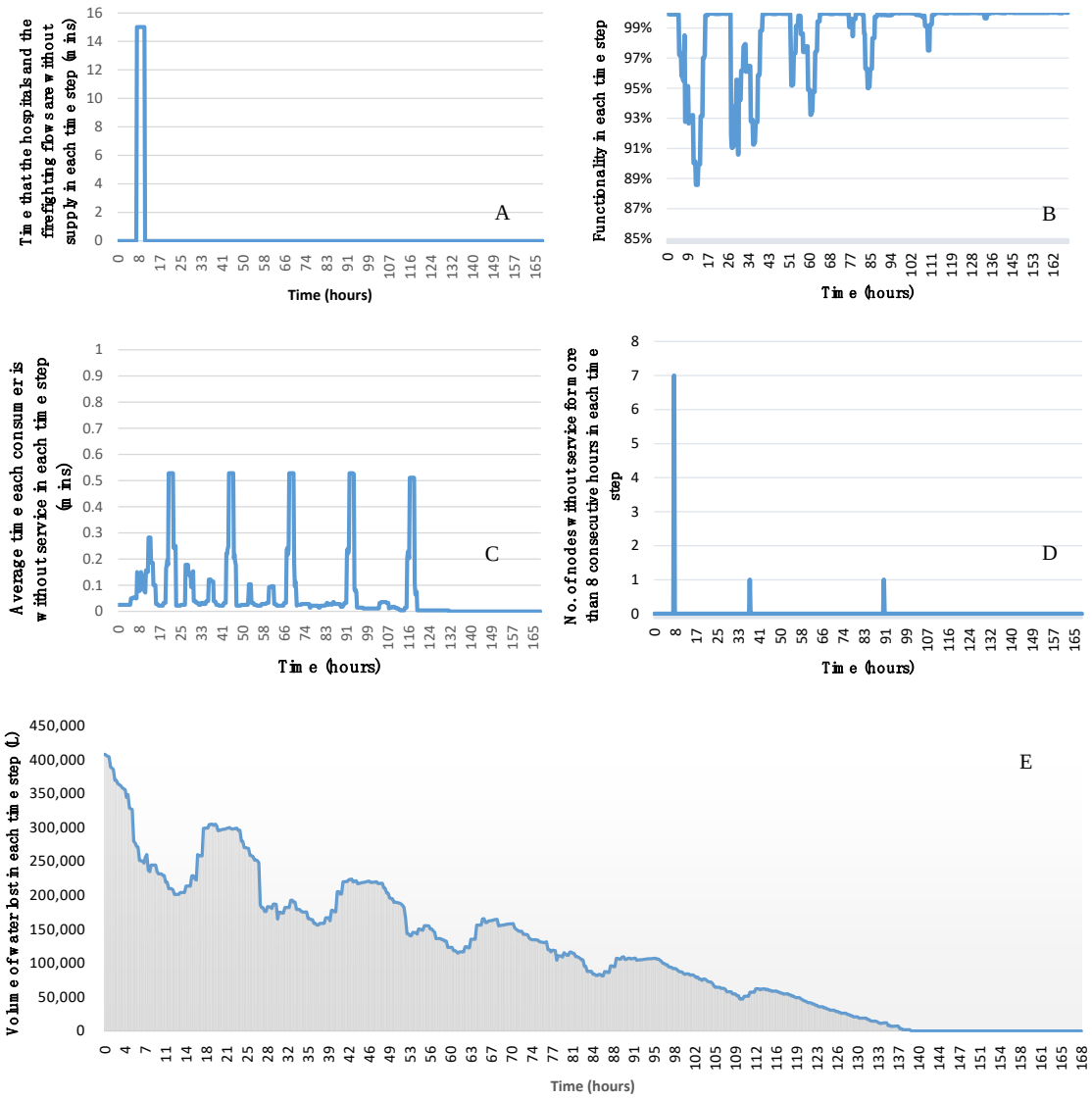

Figure D3. The change of evaluation index with time step for scenario 3. A) Time that the hospitals and the firefighting flows are without supply in each time step (mins); B) Functionality in each time step (%); C) Average time each consumer is without service in each time step (mins); D) No. of nodes without service for more than 8 consecutive hours in each time step; and E) Volume of water lost in each time step (L)

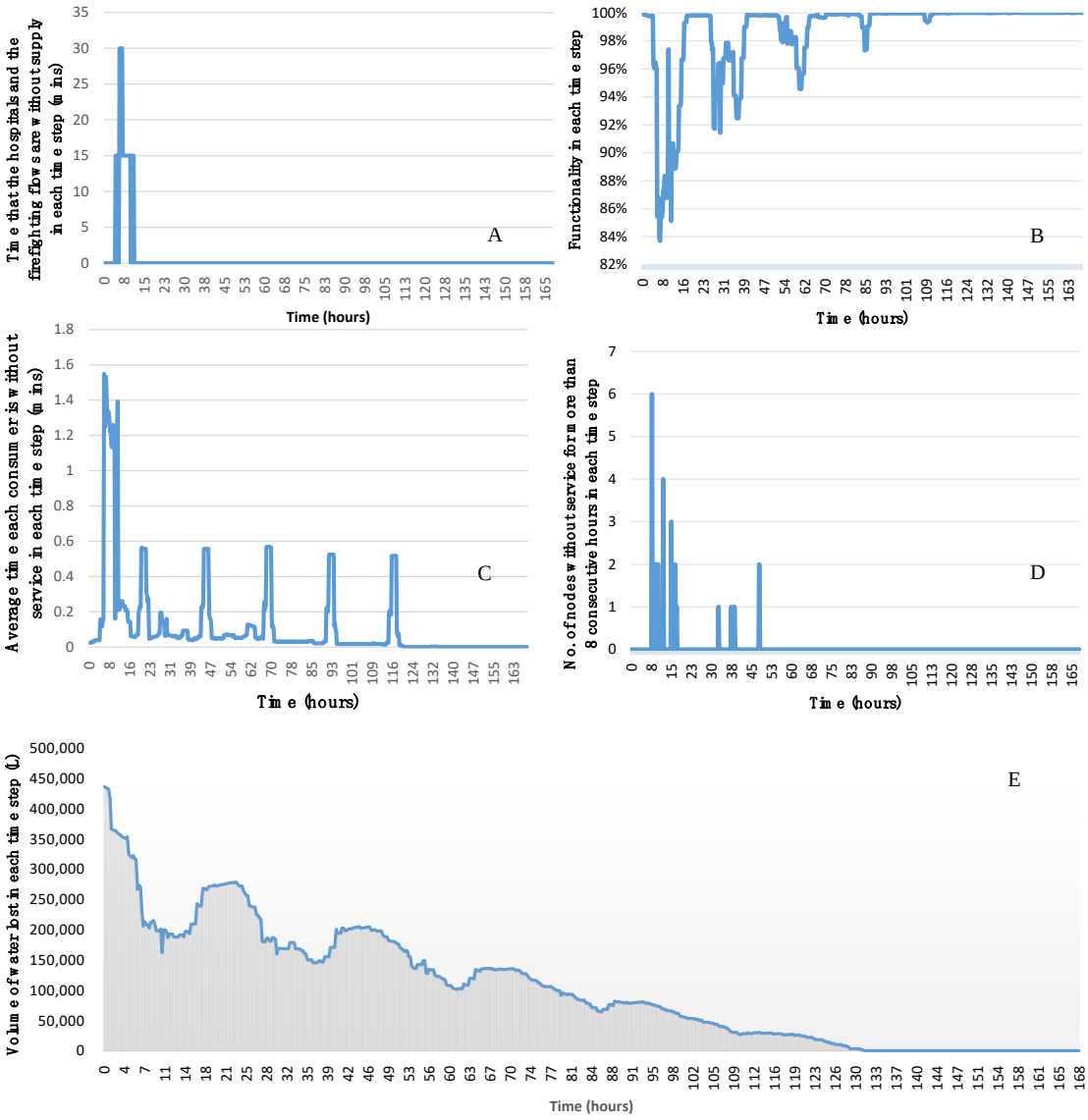

Figure D4. The change of evaluation index with time step for scenario 4. A) Time that the hospitals and the firefighting flows are without supply in each time step (mins); B) Functionality in each time step (%); C) Average time each consumer is without service in each time step (mins); D) No. of nodes without service for more than 8 consecutive hours in each time step; and E) Volume of water lost in each time step (L)

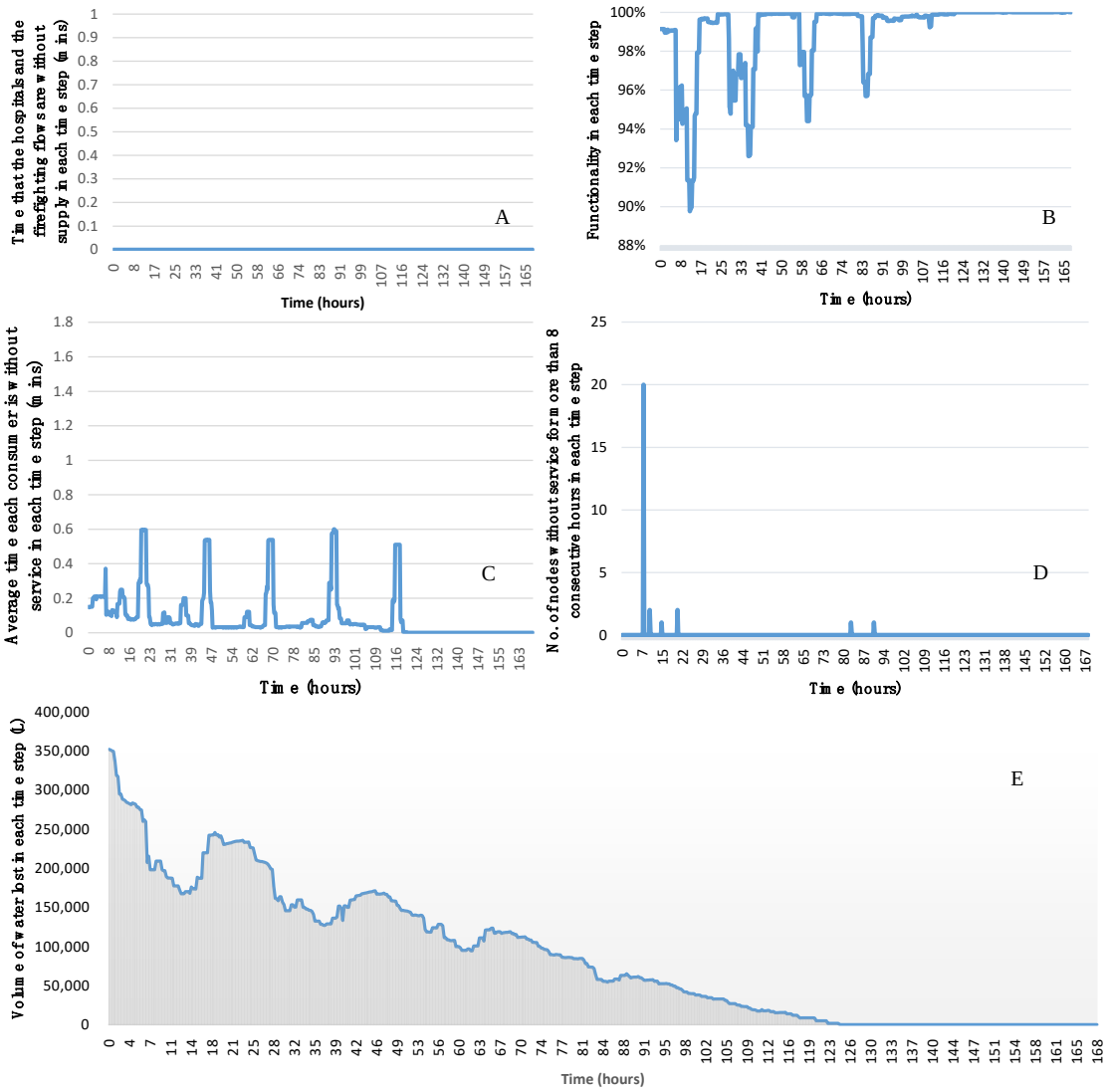

Figure D5. The change of evaluation index with time step for scenario 5. A) Time that the hospitals and the firefighting flows are without supply in each time step (mins); B) Functionality in each time step (%); C) Average time each consumer is without service in each time step (mins); D) No. of nodes without service for more than 8 consecutive hours in each time step; and E) Volume of water lost in each time step (L)